DESIGN AND CONSTRUCTION OF LARGE PANEL CONCRETE STRUCTURES

Contract No. H-2131R

supplemental report B

Horizontal Joint Tests

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FOREWORD

Traditionally, multi-story buildings are so constructed that if a load-carrying member collapses, the entire structure does not: it has an inherent structural integrity. But construction using large-panel concrete members is not traditional. Builders cannot necessarily depend on the new structure's inherent integrity.

To avoid potential problems, the Office of Policy Development and Research has undertaken an extensive research program on large-panel concrete structures. This report, the sixth of nine, deals with horizontal joint tests, and most importantly with the connection of walls to floors.

The research program was supervised for HUD by the late William J. Werner and continued by Ronald J. Morony. Designers, manufacturers, and builders have reason to be grateful to them.

Donna E. Shalala
Assistant Secretary for Policy
Development and Research

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ABSTRACT

This report describes full-scale tests conducted on horizontal joints to investigate the behavior of wall-to-floor connections in large panel structures. Splitting tests were also made to determine the optimum amount of reinforcement in the ends of the walls to limit splitting. Controlled variables included in the test program were strength of grout in the joint, amount of transverse wall reinforcement, and presence of applied floor moment and rotation. Effects of test variables on joint strength are discussed and a design procedure is proposed.

EXECUTIVE SUMMARY

This experimental report on horizontal joints is part of a series of reports leading to the development of a "Methodology for the Design and Construction of Large Panel (LP) Structures." The objective of the tests described in this report was to investigate the behavior of interior and exterior wall-to-floor connections in LP structures.

Sixteen full-scale joint tests and seven splitting tests were made. Joint specimens consisted of an assembly of precast hollow-core floor slabs and precast concrete wall elements forming a wall-to-floor connection. The specimens represented a short length of wall from a large panel building. Grout was used to fill the joint between the ends of the floor slabs. Transmission of vertical load through the joint was investigated by applying vertical compressive force in increments.

Seven simplified splitting tests were made on specimens consisting of a short wall element loaded to represent partial surface loading present in the joint. The objective was to determine the optimum amount of transverse reinforcement in the ends of the wall panels to limit splitting.

The experimental program included the following controlled test variables:

- strength of grout in the joint,
- amount of transverse wall reinforcement,
- filled or unfilled slab cores, and
- applied floor moment and rotation.

Compressive strength of concrete used in the wall panels and the precast hollow-core slab elements was held constant.

Depending upon the provided combination of test variables mentioned above, the following damage patterns were observed at ultimate load:

- grout crushing,
- wall splitting, and
- slab crushing.

Test results indicated that when high-strength grout was used in the joint, the presence of transverse wall reinforcement increased overall strength of the connection. The optimum amount of wall reinforcement depended on strength of grout in the joint. With low-strength grouts, the joint strength was increased substantially by filling the slab cores with grout in the connection region. However, in the case of high-strength grouts, filling the cores was only effective if the wall panels were adequately reinforced against splitting.

The following conclusions are based on results of the experimental program:

1. Joint capacity increases with grout compressive strength, when joint strength is controlled by grout crushing.

2. Wall splitting does not occur when low-strength grout is used.

3. For unreinforced walls, as the grout strength approaches wall compressive strength, the mode of joint behavior changes from grout crushing to wall splitting. Therefore, grout strengths higher than wall strengths do not increase joint capacity unless the walls are adequately reinforced. The amount of wall reinforcement required to prevent splitting increases with grout strength.

4. Filling slab cores with grout directly affects joint strength when low strength grouts are used. However, when medium or high strength grouts are used, filled cores are effective only if the wall panels are reinforced.

5. Inadequate dry packing below the upper wall panel leads to a substantial loss of joint strength.

6. Floor moment and rotation do not have a significant effect on joint capacity.

Various design methods to determine the load capacity of horizontal joints are discussed. A new design procedure is proposed. Comparisons of measured and calculated strengths for various joint specimens are made.

In addition, details of the experimental program and properties of grout used in the joints, are included as appendices to the report.

Detailed recommendations for specific analysis and design of connections are presented in Report 5.

OVERALL PROGRAM OBJECTIVES

The term "large panel" (LP) concrete structure is used to describe a structural system composed of precast vertical wall panels with precast floors and roofs of panels or planks assembled as shown in Fig. 1. These prefabricated component buildings can be considered to be the industrialized form of conventional cast-in-place structural wall (egg crate) construction. Large panel buildings are differentiated by the general arrangement of load-bearing walls as shown in Fig. 2:

(a) Cross wall system: in this most prevalent form, load-bearing cross walls are perpendicular to the longitudinal axis of the building.

(b) Spine wall system: for this form load-bearing walls are parallel to the longitudinal axis of the structure.

(c) Mixed systems: a combination of cross wall and spine wall systems is used.

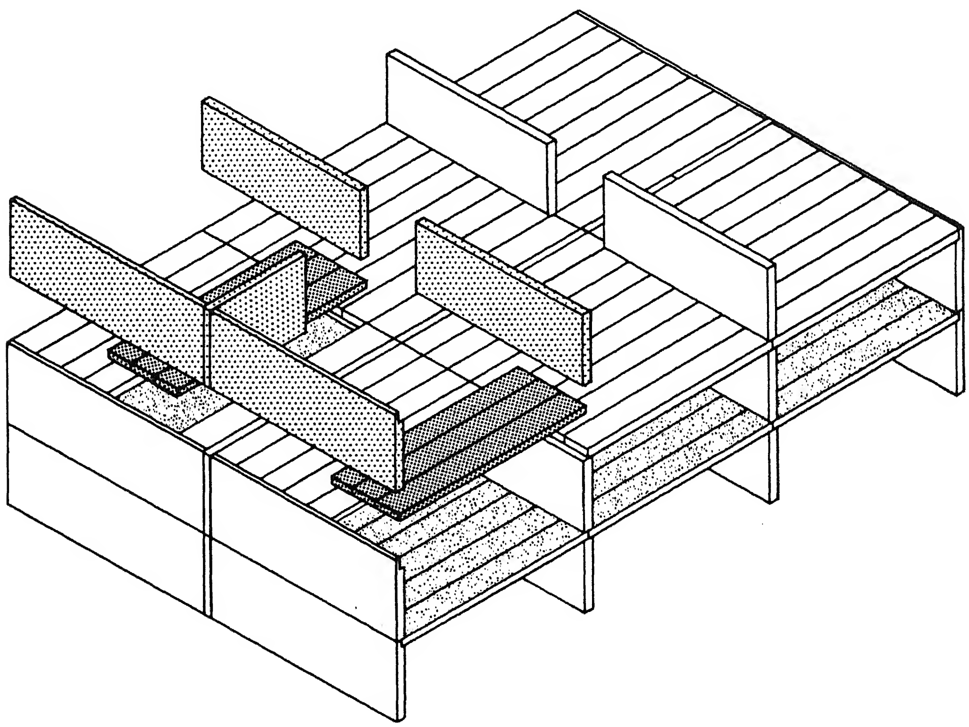
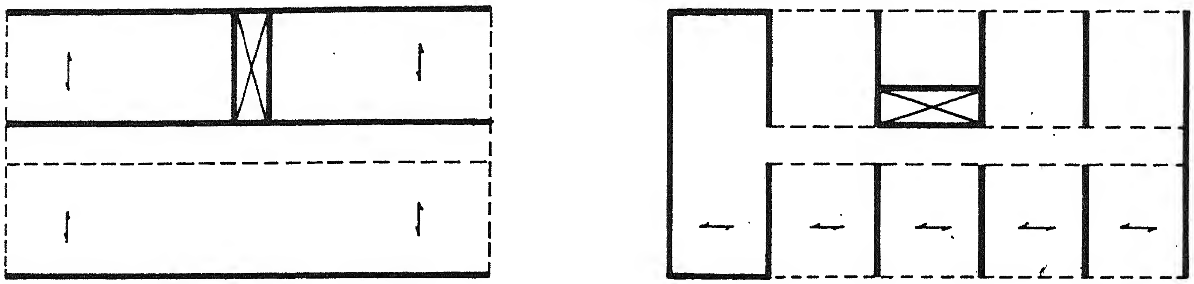


Fig. 1 Isometric View of Idealized Large Panel Structure



(a) Cross Wall System (b) Spine Wall System

Fig. 2 Idealized Plan Arrangement of Structural Wall Panels in Large Panel Structures

In most LP systems, the walls transfer their loads directly to the substructure without an intermediate frame. This form of construction restricts open plans at any level. Thus it is most typically suited for multistory housing where walls have to be provided between apartments to resist fire and noise transmission. Construction types considered under this investigative program include solid, sandwich, ribbed, hollow core or composite wall panels. Solid, hollow core, or ribbed floor units with or without cast-in-place topping are also included. All elements can be either prestressed or conventionally reinforced.

The overall program objective is to develop minimum criteria for the design and construction of large panel structures. These criteria are being developed to ensure structural safety and serviceability of LP residential buildings, while also providing minimum performance requirements to be used by designers and developers of innovative systems. Development of the criteria will also expand the knowledge of design and construction of large panel structures to a level comparable with that existing for conventional cast-in-place concrete or steel structural systems.

1. INTRODUCTION

From a structural viewpoint, the essential difference between a cast-in-place concrete structure and a precast large panel structure is the nature of connections between elements. The function of connections is to transfer forces from one element to another. Ability of large panel structures to perform satisfactorily under all conditions of loading depends upon the integrity of the connections. Connections must transmit gravity loads from floor to wall elements, from wall to wall, and from wall elements to the foundation. They must also provide for interaction between the various elements and for sufficient ductility in resisting lateral loads. If the connections are inadequate, strength of the adjoining elements may not be fully utilized.

Connections may be classified [1] as interior horizontal wall-to-floor, exterior horizontal wall-to-floor, horizontal floor-to-floor, and vertical wall-to-wall. The main objective of the tests described in this report was to investigate behavior of wall-to-floor connections commonly used in the United States. The report covers tests of both interior and exterior horizontal joints. A single configuration of "Platform Joints" was tested. Compressive strength of concrete in wall panels and hollow-core slabs, and strength of dry-packed mortar below the upper wall panel were held constant throughout the test series.

Specific analysis and design techniques for types of connections commonly used in LP structures, are presented in Report 5[2].

2. EXPERIMENTAL PROGRAM

Details of the test specimens for interior and exterior joints are shown in Figs. 3 and 4, respectively. Controlled variables included in the test program were:

(a) strength of grout in the joint,
(b) amount of transverse reinforcement at the top and bottom of wall panels,
(c) filled or unfilled slab cores, and
(d) applied floor moment and rotation.

Design compressive strength of concrete used in the wall panels and the precast floor slab elements was about 5000 psi (34.5 MPa).

2.1 Test Specimens

Sixteen full-scale wall-to-floor connections and seven simplified wall splitting specimens were tested. In the connection tests, floor slab elements consisted of precast concrete hollow-core planks. Wall elements were blocks of precast concrete. Nominal thickness and width of floor planks were 8 in. (203 mm) and 24 in. (610 mm), respectively.

Detailed descriptions of materials, specimen fabrication, instrumentation, and test procedures are given in Appendix C.

2.1.1 Specimen JM-1

Before beginning the main test program, Specimen JM-1 was tested to determine the influence of applied floor moment and joint rotation on joint strength. The test was performed using 15-ft (4.57 m) long slabs on each side of the connection. Test setup and loading arrangement are shown in Fig. 5. Vertical load was applied to the wall in increments by a hydraulic testing machine. Hydraulic rams[3] were used to apply floor moment by applying load at a

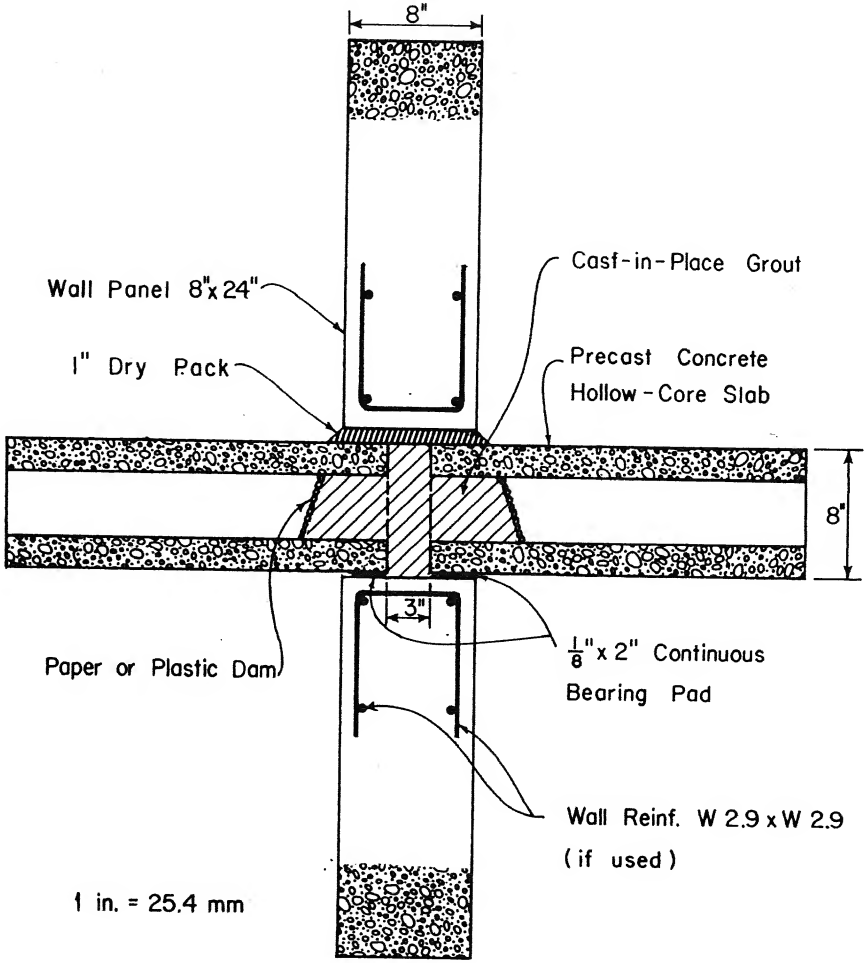


Fig. 3 Interior Joint Specimen
with Filled Slab Cores

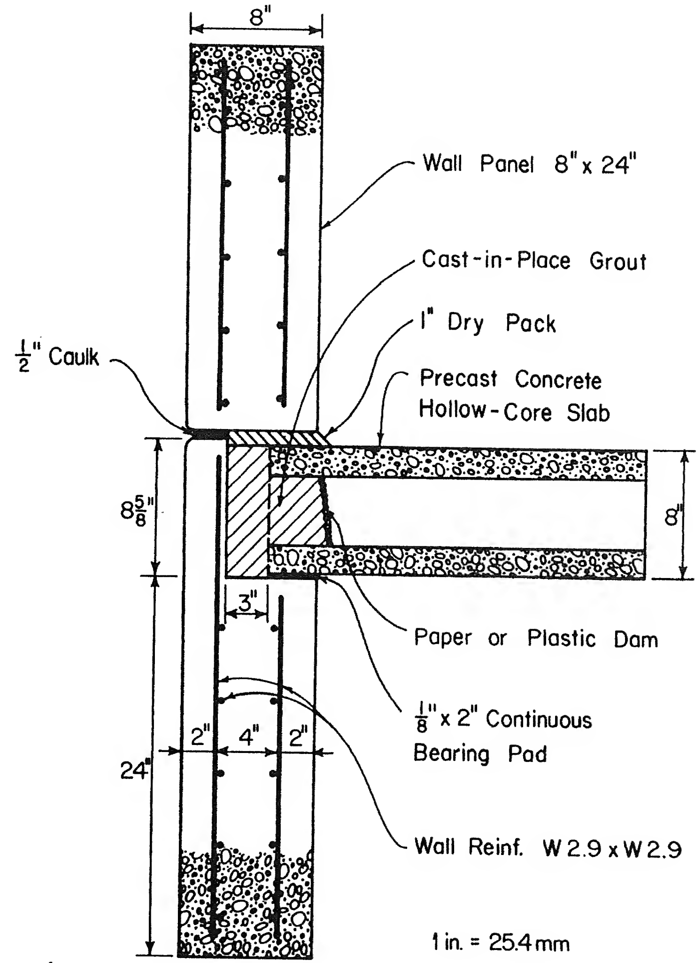


Fig. 4 Exterior Joint Specimen
with Filled Slab Cores

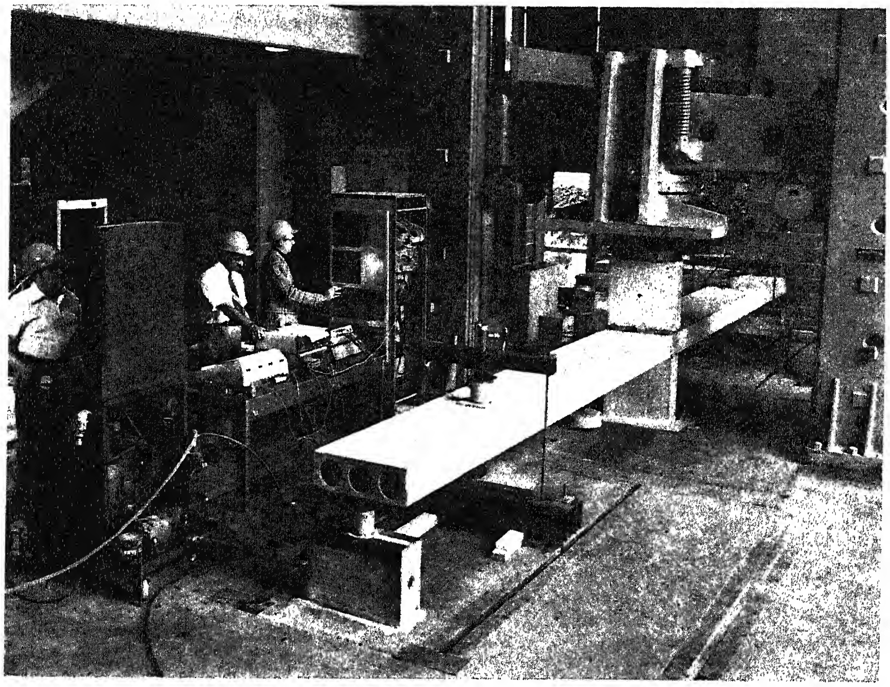


Fig. 5 Test Setup for Specimen JM-1

predetermined location. This load was applied in a specific sequence of loading and unloading as the axial wall load was increased. The load on the slabs was measured by a pair of load cells[4].

Negative moment introduced at the joint was slightly less than the calculated cracking moment for a 24-in. (0.61 m) wide unreinforced slab. Each floor load was positioned at about the third point from the simply supported end of the slab. This provided a moment to shear ratio of about 5 at the joint. The figure was based on calculations for a 30-ft. (9.14 m) long slab, assumed fixed at both ends.

For Specimen JM-1, grout strength was 3000 psi (20.7 MPa). Both top and bottom walls were unreinforced.

2.1.2 Series A - Splitting Tests

Splitting tests were performed to determine the optimum amount of transverse reinforcement needed in the ends of the walls to limit splitting. Wall blocks were plastered to the base of the testing machine. Vertical load was applied on top through a 3-in. (76 mm) wide by 24-in. (610 mm) long steel plate. This loading area corresponded to the area loaded by the grout column in a complete joint. Figure 6 shows the test setup for this series. Concrete compressive strength and amount of reinforcement provided for each specimen in this series are shown in Table 1.

2.1.3 Series J and B - Interior Joint Tests

Ten tests were conducted in Series J and B. Figure 7 shows the test setup. A comparison of test results from trial Specimens JM-1 and J-1 indicated that applied floor moment and rotation did not reduce joint strength. Consequently, short slabs, without any applied floor moment, were used for the remaining tests. However, the slab blocks were supported at the free ends to prevent rotation.

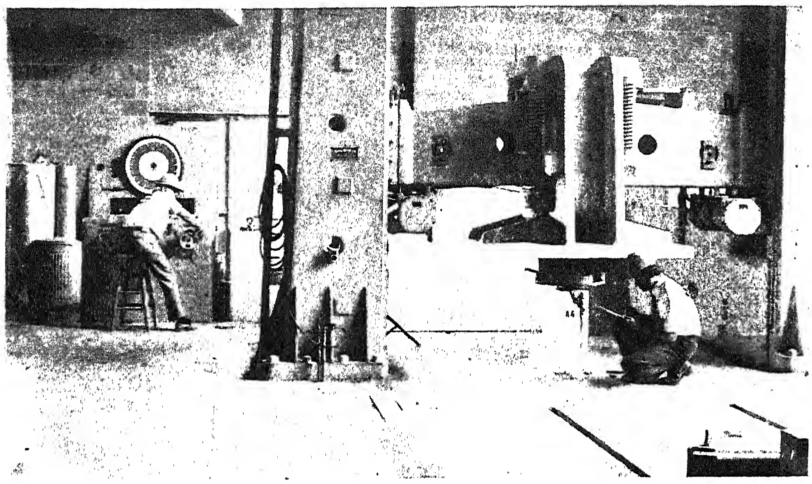


Fig. 6 Splitting Wall Test Setup

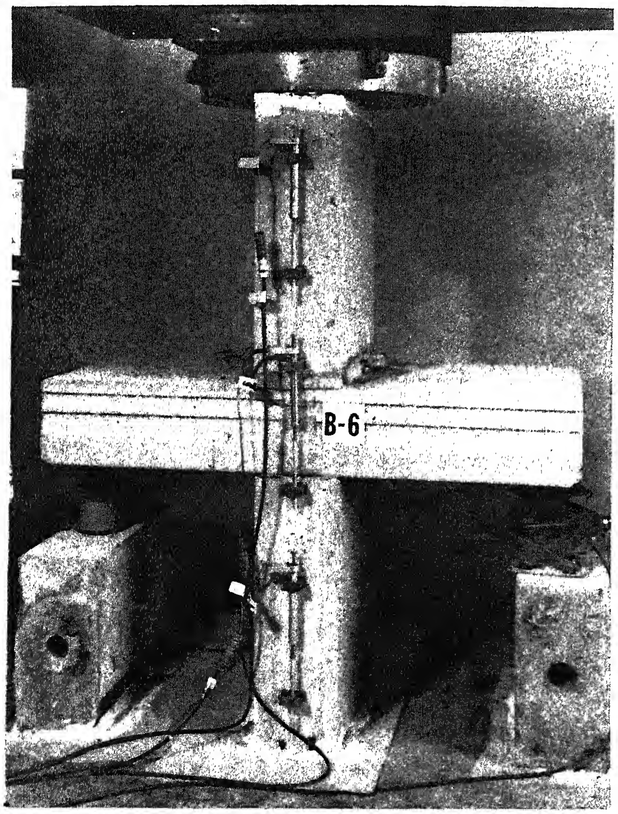


Fig. 7 Interior Joint Test Setup

TABLE 1 - DETAILS OF SPLITTING TESTS - SERIES A

Specimen Number	Concrete Strength* (psi)	Amount of Wall Reinforcement ($in.^2$)	Size of Welded Wire Fabric**	Number of Wires
A-1	5040	0	0	0
A-2	4910	0.041	6x6 - W2.1xW2.1	2
A-7	5040	0.082	6x6 - W2.1xW2.1	4
A-3	5040	0.116	6x6 - W2.9xW2.9	4
A-4	4910	0.144	6x6 - W2.1xW2.1	7
A-5	4910	0.227	6x6 - W2.1xW2.1	11
A-6	4910	0.309	6x6 - W2.1xW2.1	15

*Average compressive strength measured on six 6x12-in. cylinders.

**6x6-in. mesh with W2.1 and W2.9 wires corresponds to diameters of 0.162 and 0.192 in., respectively.

Metric equivalents: 1 psi = 6.89 kPa
1 in. = 25.4 mm

Controlled test variables were:

(a) strength of grout in the joint,

(b) amount of transverse wall reinforcement, and

(c) filled or unfilled slab cores.

Grout strength, amount of wall reinforcement and other details for different interior joint tests are given in Table 2.

2.1.4 Series E - Exterior Joint Tests

Details of exterior joint test specimens are shown in Fig. 4. Five full-scale tests were conducted. Controlled variables included in the test program were similar to those for interior joints. The test setup is illustrated in Fig. 8. The layout of instrumentation was similar to the interior joints.

Grout strength, amount of wall reinforcement and other details for exterior joints are given in Table 3.

TABLE 2 - DETAILS OF TEST SPECIMENS - INTERIOR JOINTS

Specimen Number	Wall Panel Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** ($in.^2$)	Slab Cores Filled or Unfilled	Remarks
JM-1***	4860	3000	0	Filled	Poor Quality Dry Packing
J-1	4860	3000	0	Filled	
B-6	5380	2730	0	Unfilled	--
B-7	5380	3240	0.116	Unfilled	--
B-5	5420	2980	0	Filled	--
B-2	5310	3260	0.116	Filled	--
B-3A	4810	4510	0.116	Unfilled	--
J-2	4820	5000	0	Filled	--
J-3	4820	5000	0.116	Filled	--
B-4	5310	6800	0.116	Filled	--
B-1	4810	4510	0.116	Filled	No Grout Column

*Average compressive strength measured on nine 6x12-in. cylinders.

**6x6-W2.9xW2.9, four cross wires per wall, $A_s = 4 \times 0.029 = 0.116$ $in.^2$

***Specimen with long slabs and applied floor moment.

Metric Equivalents: 1 psi = 6.89 kPa.
1 in = 25.4 mm

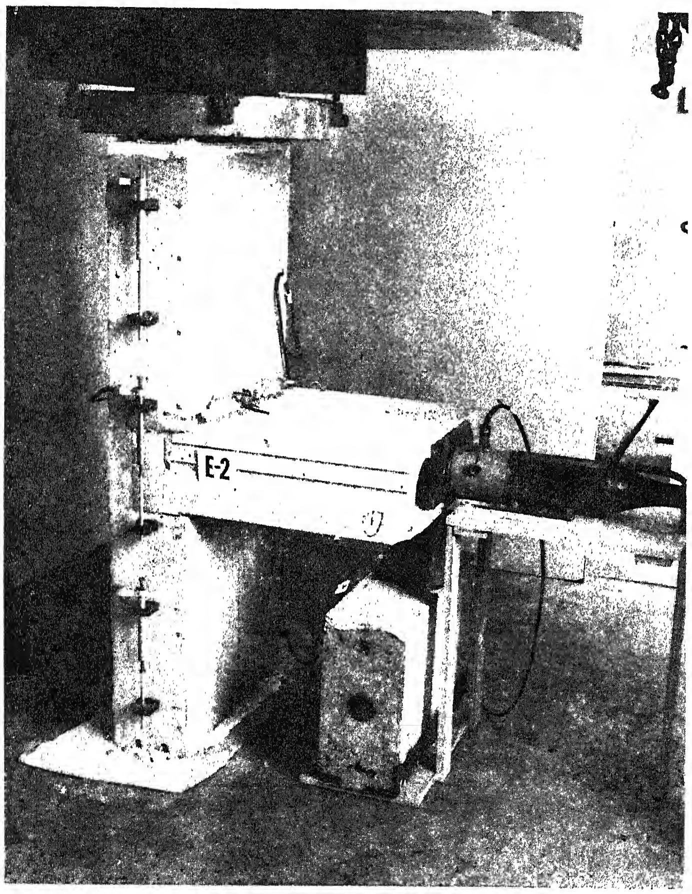


Fig. 8 'Exterior Joint Test Setup

TABLE 3 - DETAILS OF TEST SPECIMENS - EXTERIOR JOINTS

Specimen Number	Wall Panels Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in.^{2})	Slab Cores Filled or Unfilled
E-1	5420	2980	0	Filled
E-2	5180	2840	0	Unfilled
E-3	5180	4770	0	Unfilled
E-4	4900	4630	0	Filled
E-5	4900	4510	0.116	Filled

*Average compressive strength measured on six 6x12-in. cylinders.

**6x6-W2.9xW2.9, four cross wires per wall panel, A_s = 4x0.029 = 0.116 in.^{2}

Metric Equivalents: 1 psi = 6.89 kPa
1 in. = 25.4 mm

3. TEST RESULTS - INTERIOR JOINTS

3.1 Specimen Strength

Measured ultimate loads and relevant data are listed in Table 4. For convenience, these results are expressed both as ultimate load, P_u, and as average wall stress. The latter was obtained by dividing the ultimate load by the bearing area of the wall panel. Also given in Table 4 are the behavior observations at ultimate load. These are discussed further in Section 3.3.

Measured values of the ultimate load versus wall reinforcement for the splitting test series are shown in Fig. 9. The minimum amount of reinforcement to give slightly higher ultimate load in splitting tests was determined as 0.116 in.^{2} (75 mm^2). This reinforcement was found sufficient to limit wall splitting in the subsequent joint tests when low to medium strength grouts were used.

3.2 Joint Shortening

Variation of vertical shortening, top wall horizontal strain, and horizontal crack widths with applied loads for Specimen J-2 are shown in Figs. 10, 11, and 12, respectively. Average vertical strain for joint and wall panels was calculated by dividing the total shortening, measured using LVDT's(3) by the 10 in. (254 mm) gage length. Plots for other tests showed similar trends.

Joint shortening is due to compression of the grout column and the adjacent end of each of the floor slabs. Grout strength had a major influence on the amount of shortening. Overall shortening was greater for low-strength grouts. For similar conditions of grout strength and wall reinforcement, joint shortening in specimens with unfilled slab cores was at least 33% higher than those with cores filled. Transverse wall reinforcement reduced measured wall shortening. This was probably due to decreased splitting in reinforced wall panels.

TABLE 4 - TEST RESULTS - INTERIOR JOINTS

Specimen Number	Ultimate Load P_u (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
JM-1	350	1820	4860	3000	Filled	Wall Splitting+	Poor Dry Packing (inadequately packed)
J-1	300	1560	4860	3000	Filled	Wall Splitting+	
B-6	343	1790	5380	2730	Unfilled	Grout Crushing	--
B-7*	360	1870	5380	3240	Unfilled	Grout Crushing	--
B-5	440	2290	5420	2980	Filled	Grout Crushing & Wall Splitting	Both Upper & Lower Walls Split
B-2*	460	2400	5310	3260	Filled	Grout Crushing	--
B-3A*	440	2290	4810	4510	Unfilled	Grout Crushing	--
J-2	465	2420	4820	5000	Filled	Wall Splitting+	--
J-3*	520	2710	4820	5000	Filled	Grout Crushing	--
B-4*	525	2730	5310	6800	Filled	Lower Wall Splitting	Upper Wall & Grout Uncracked
B-1*	266	1380	4810	4510	Filled	Slab Crushing	No Grout Column, Slab Cores Filled

*Wall Panels reinforced with 6x6 - W 2.9 X W 2.9, $A_s = 0.116$ in.^{2}

**Average wall stress obtained by dividing the ultimate load by the bearing area of the wall panel (bearing area is 24 x 8 in.).

+Upper wall splitting.

Metric equivalents: 1 kip = 4.448 kN
1 psi = 6.89 kPa
1 in. = 25.4 mm

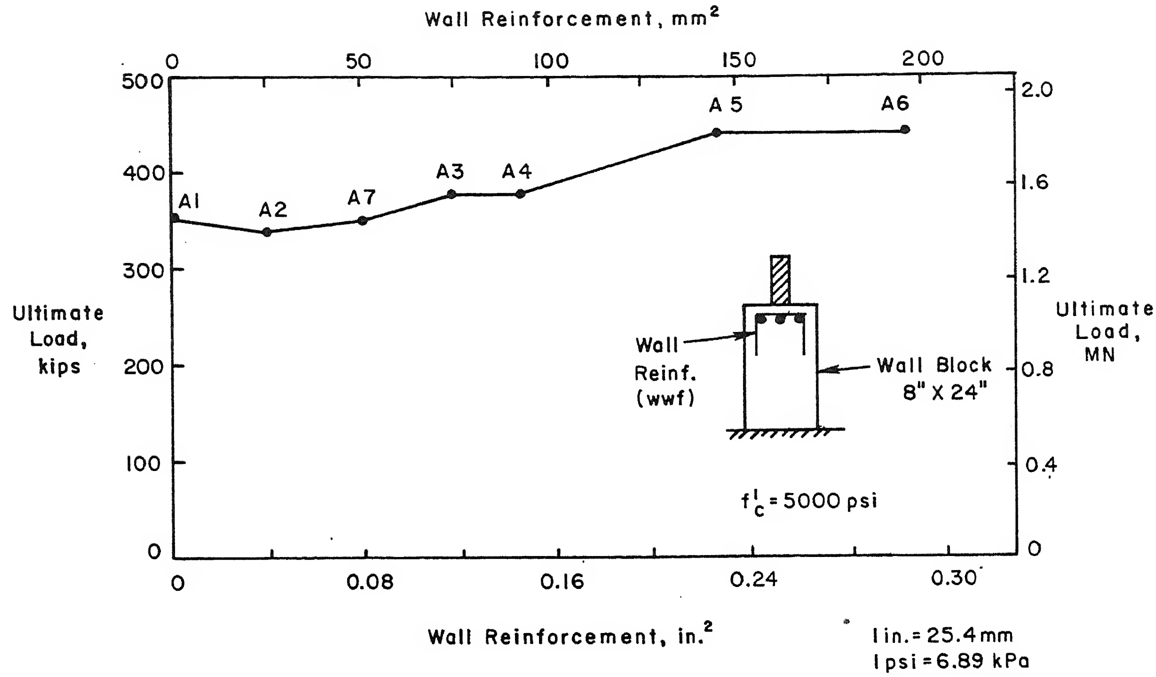


Fig. 9 Splitting Tests - Series A

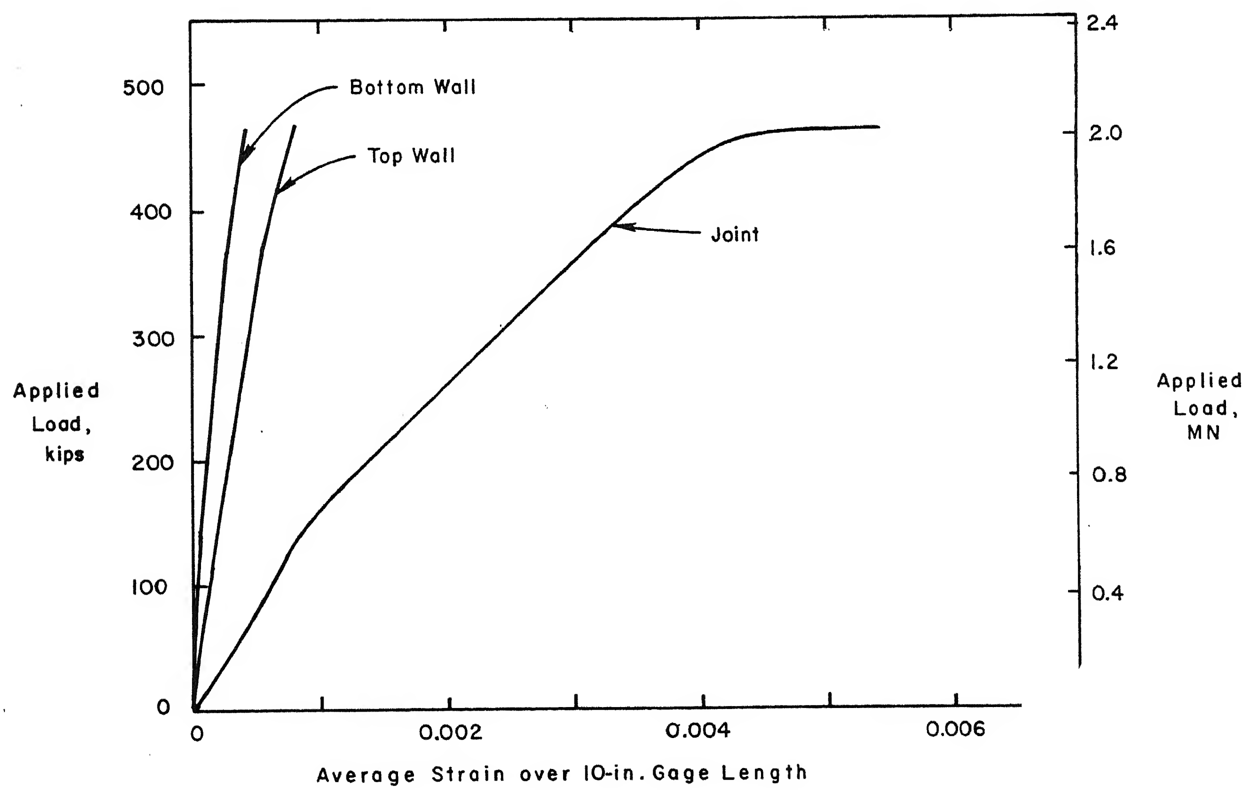


Fig. 10 Load versus Shorte

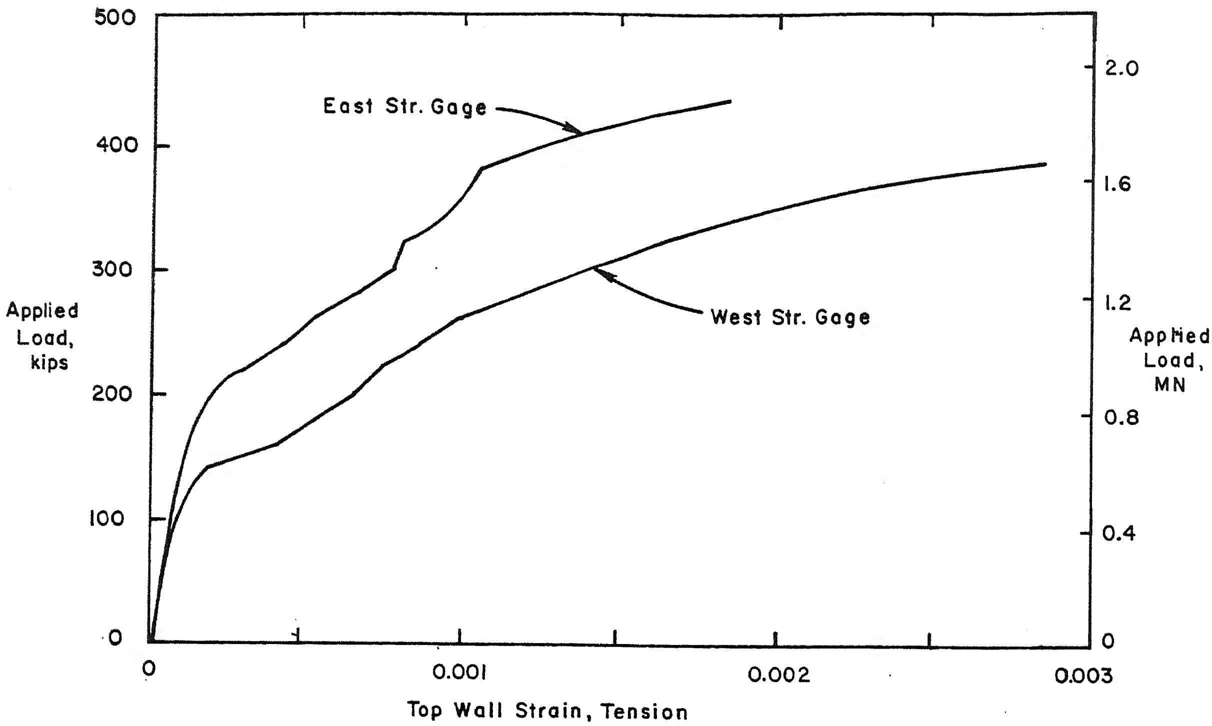


Fig. 11 Load versus Top Wall Strain for Specimen J-2

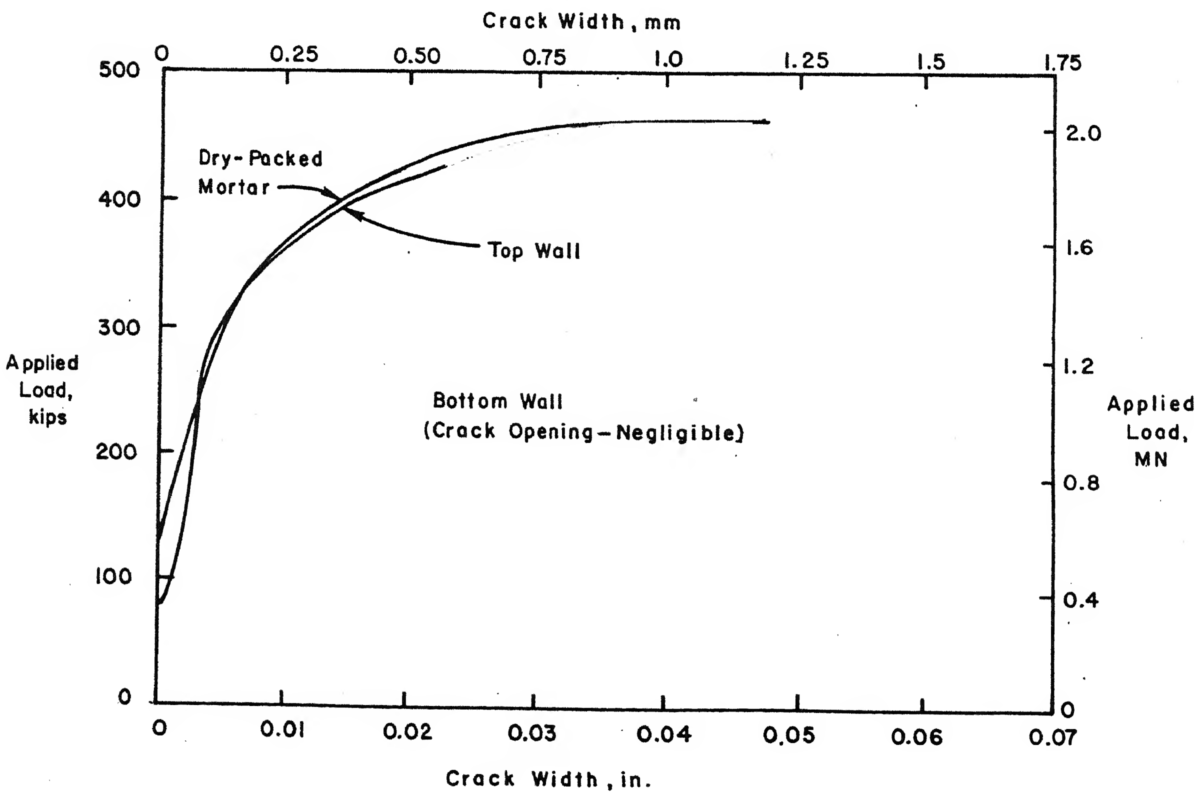


Fig. 12 Load versus Wall Separation for Specimen J-2

3.3 General Behavior

Vertical load can pass through an interior joint from the upper wall to the lower wall in either of two distinct fashions.

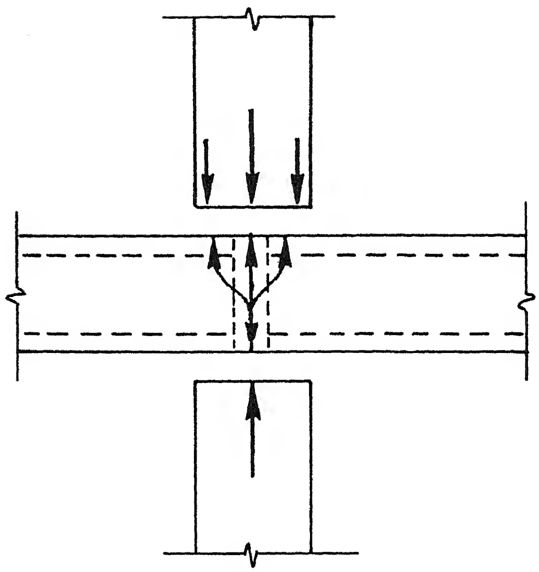
In the first case shown schematically in Fig. 13(a), the joint functions in a monolithic fashion. Stresses across the top of the joint are for the most part uniform. However, due to soft bearing pads beneath the slabs, the load is funnelled into the bottom of the grout column causing a stress concentration in the lower portion of the joint as shown. Shear stresses are transferred at the slab-grout column interface.

In the second case, shown schematically in Fig. 13(b), the joint consists of three distinct vertical "columns": a grout column in the center with a column on either side. The outer columns consist of the supported slabs and bearing pads. The amount of load that each "column" supports varies with the stiffness of that column in relation to the total joint. Uniform material properties produce generally uniform stresses across the joint, while greatly differing properties cause stress concentrations.

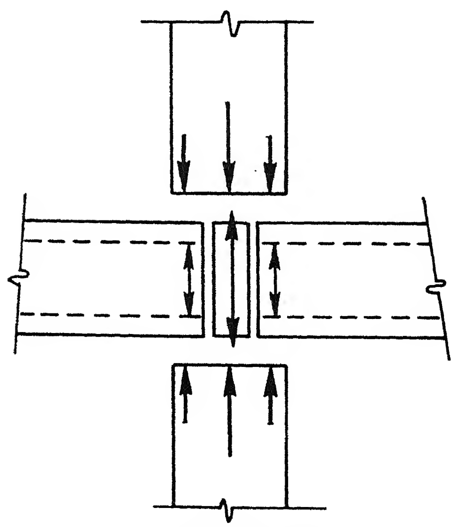
For a particular interior joint, load flow patterns and behavior are governed by four variables:

1. Compressive strength of the grout as related to the compressive strength of the wall and slab concrete is one variable. For purposes of discussion, "low", "medium", and "high" strength grouts are defined as having compressive strengths, respectively, less than, equal to and greater than the strength of the slab and wall concrete. The slab and wall concrete are assumed to have equal strength.

2. Extension of the grout into the hollow cores of the slabs is another variable. Hollow cores are considered filled if the grout extends at least to the plane of the face of the wall.



(a) Before Cracking



(b) After Cracking

Fig. 13 General Behavior - Interior Joints

3. Presence of split-resistant reinforcement in the walls is a third variable. The reinforcement consists of nominal transverse welded wire fabric as shown in Fig. 3.

4. Stress level in the joint is a fourth variable.

The effects of these variables are discussed in the following sections.

3.3.1 Case 1: Low Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

For Case 1 shown in Fig. 14(a) load flow is through discrete vertical columns. Since the slab cores are unfilled and the slabs themselves are supported on soft bearing pads, the grout column is independent of the slab and carries most of the load. With grout strength less than the wall strength, increasing load produces grout column crushing, identified as Stage 1. With the loss of the grout column, load is transferred to the two slab ends. Due to their lower net area these eventually crush before damaging the wall. This is identified as Stage 2. Since the capacity of the grout column is generally greater than that of the combined slab ends, maximum capacity is reached at Stage 1.

Stresses in the wall panels never control. Consequently, the behavior and capacity of this joint configuration are not affected by reinforcing. This behavior was observed in Specimens B-6 and B-7. Specimen B-6 after testing is shown in Fig. 15(a).

3.3.2 Case 2: Low Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

For Case 2 with filled cores as shown in Fig. 14(b), the joint behaves initially as a monolithic element. The funnelling effect is accomplished through shear between the grout column and the grout cores. Vertical stress is initially uniform at the top of

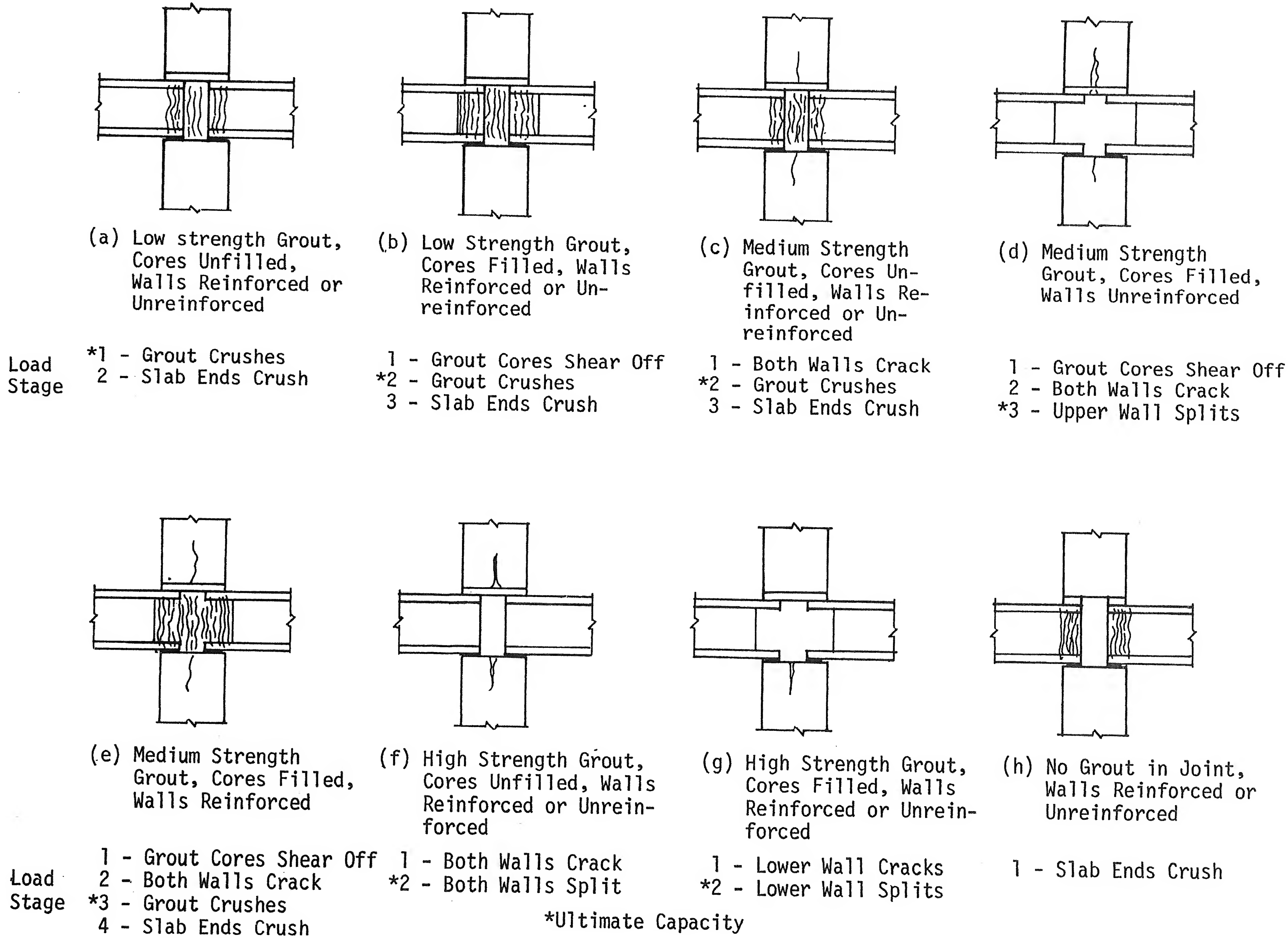
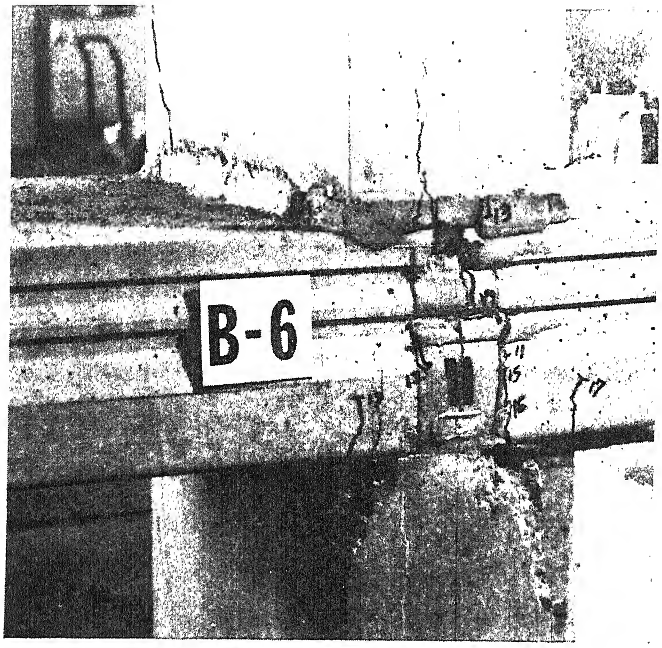
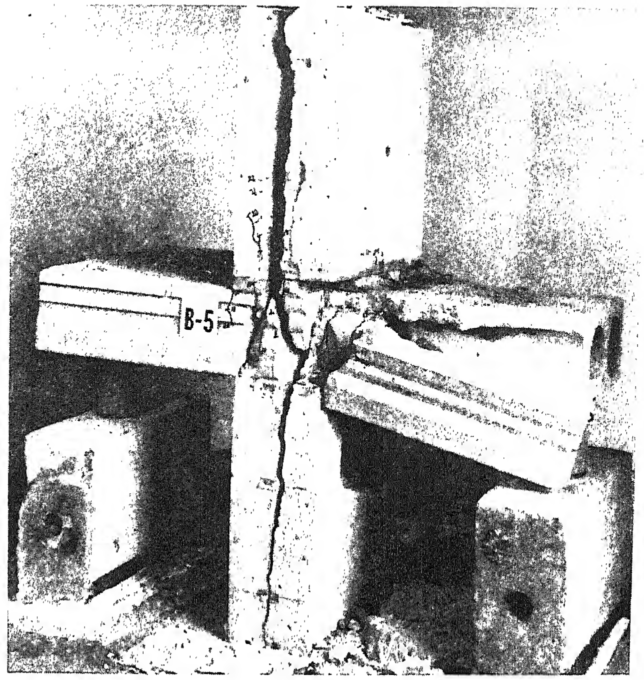


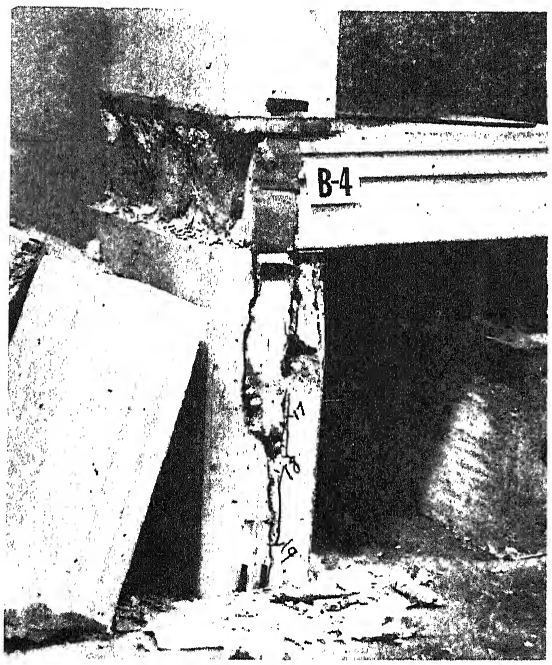
Fig. 14 Behavior at Successive Load Stages - Interior Joints



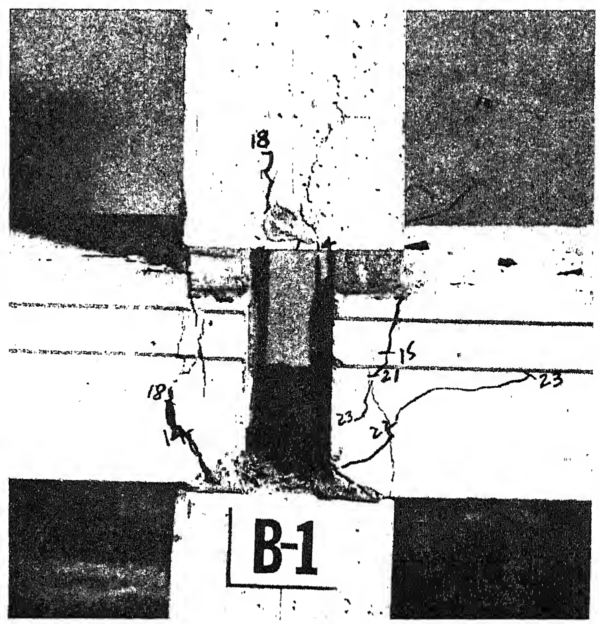
(a) Grout Crushing



(b) Upper Wall Splitting



(c) Lower Wall Splitting



(d) Slab Crushing

Fig. 15 Damage Patterns at Ultimate Load - Interior Joints

the joint and concentrated at the bottom of the grout column in the joint. As load is increased, shear capacity of the low strength grout cores is reached and the grout cores are sheared off from the grout column. This is identified as Stage 1.

Following Load Stage 1, the load flow is through discrete vertical columns. Due to the soft bearing pads under the slab ends, the grout column carries most of the load. With grout strength less than wall strength, increased load produces grout crushing, identified as Stage 2, and load is transferred to the slab ends. Although the slab ends have additional strength due to the filled cores, they are still weaker than the wall elements. Crushing of the slab ends is the final stage. This type of behavior was evident in Specimens B-2 and B-5. Secondary splitting of the wall also occurred in Specimen B-5, shown in Fig. 15(b). As in Case 1, the maximum joint capacity is reached when grout is crushed at Stage 2. Stresses in the wall panels never become critical, consequently reinforcing does not affect behavior or capacity in this joint configuration.

3.3.3 Case 3: Medium Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

For Case 3 shown in Fig. 14(c), load flow is through discrete vertical columns. The soft bearing pads and unfilled cores of the slab ends cause the grout column to support most of the load. This leads to vertical stress concentrations at the wall ends, and induces horizontal tensile stresses in the walls. Increased load cracks the upper and lower walls, identified as Stage 1. Further increase in load, however, causes grout crushing before either wall splits. This is identified as Stage 2. Grout crushing is followed by load transfer to the slab ends and eventual slab end crushing, identified as Stage 3. The capacity of the grout column is greater than that of the combined slab ends. As a result, maximum load is reached at Load Stage 2.

Tensile stresses in the wall panels are sufficient to initiate nominal cracks but not high enough to warrant reinforcing. The behavior and capacity of the joint are not expected to be changed by reinforcing. Specimen B-3A containing reinforcement exhibited this behavior.

3.3.4 Case 4: Medium Strength Grout, Cores Filled, Walls Unreinforced

For Case 4 shown in Fig. 14(d), grouted cores cause the joint to respond initially as a monolithic element. Vertical stress is uniform at the top of the joint and concentrated in the grout column at the bottom of the joint. As load is increased, shear capacity of the medium strength grout cores is reached and the grout cores are sheared off from the grout column. This is identified as Stage 1.

Following Stage 1, load flow is through discrete vertical columns. The grout column carries most of the load, but not as much as in Case 3. This is due to the increased stiffness of the grouted slab end cores versus the ungrouted cores in Case 3. The vertical stress concentrations at the wall ends caused by the grout column induce tensile stresses in the walls. Increased load causes cracks in both the upper and lower walls. This is identified as Stage 2.

For the same total vertical wall load, the grout column in this case has slightly lower stress than in Case 3. The difference is enough to split the unreinforced walls, identified as Stage 3. This behavior was observed in Specimen J-2, where the upper wall split.

3.3.5 Case 5: Medium Strength Grout, Cores Filled, Walls Reinforced

This joint configuration, shown in Fig. 14(e), is identical to that of Case 4 with the exception of the addition of transverse splitting reinforcing in both upper and lower wall panels. Behavior is also identical to that of Case 4 through Load Stage 2. As the load is

increased beyond Stage 2, the nominal reinforcement limits the wall cracking and forces the failure back into the joint in the form of grout crushing, identified as Stage 3. Load is then transferred into the slab ends which also eventually crush. This is identified as Stage 4. The capacity of the grout column confined between the slab ends, is generally higher than that of the combined grouted slab ends. Therefore, ultimate capacity is reached when grout is crushed at Stage 3. This behavior was observed in Specimen J-3.

3.3.6 Case 6: High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

For Case 6 shown in Fig. 14(f), no specimen was tested. However, based on observations from the other tests, the behavior can be anticipated. Load flow is through discrete vertical columns. The soft bearing pads and unfilled cores of the slab ends cause the grout column to support most of the load. The grout column is of higher strength than the wall. Consequently, horizontal tensile stresses in the walls, due to the vertical stress concentrations, would become critical long before the grout column capacity is reached. Increased load first cracks the upper and lower walls, and then splits them. This is identified as Stages 1 and 2, respectively. Splitting will occur whether or not the walls are nominally reinforced.

3.3.7 Case 7: High Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

For Case 7 shown in Fig. 14(g), The grouted cores cause the joint to respond as a monolithic element. Vertical stress is uniform at the top of the joint and concentrated in the grout column at the bottom of the joint. Under increasing load, the grout cores do not shear off the grout column because of the increased shear capacity of the high strength grout. Instead, the vertical stress concentration at the bottom of the joint causes horizontal tensile stress buildup in the lower wall. These latter stresses become critical

long before the grout column capacity is reached. Further increase in load first cracks the lower wall and then splits it. This is identified as Stages 1 and 2, respectively. Splitting will occur whether or not the walls are nominally reinforced. This behavior was observed in Specimen B-4, shown in Fig. 15(c).

3.3.8 Case 8: No Grout in the Joint, Walls Reinforced or Unreinforced

Case 8, shown in Fig. 14(h), represents an extreme limit of Case 1. Load flow is solely through the outside slab ends. Capacity of this joint is reached as the slab ends crush, identified as Stage 1. Stresses in the wall panel never become critical, consequently, the behavior and capacity of the joint are not altered by reinforcing. This behavior was observed in Specimen B-1, shown in Fig. 15(d).

3.4 Effect of Variables on Joint Strength

The effects of variables on interior joint strength may be summarized as follows:

1. A change in a variable to cause a more uniform vertical compressive stress across the width of the joint generally increases the vertical load-bearing capacity of the joint.

2. Under certain circumstances, control of vertical cracking in walls increases the vertical load carrying capacity of the joint.

Based on the variables examined, a list of interior joint configurations is given in Table 5. The purpose of the table is to list the joint configurations in ascending order of capacity. Behavior of joint configurations that were not tested have been estimated.

TABLE 5 - INTERIOR JOINT CONFIGURATION IN ASCENDING ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
B-1	JC1	No Grout	No	Either	8	Slab End Crushing
B-6, B-7	JC2	Low	No	Either	1	Grout Crushing
B-2, B-5	JC3	Low	Yes	Either	2	Grout Crushing
B-3a	JC4	Medium	No	Either	3	Grout Crushing
-	JC5*	High	No	No	6	Wall Splitting
J-2	JC6	Medium	Yes	No	4	Wall Splitting
-	JC7*	High	No	Yes	6	Wall Splitting
-	JC8*	High	Yes	No	7	Wall Splitting
J-3	JC9	Medium	Yes	Yes	5	Grout Crushing
B-4	JC10	High	Yes	Yes	7	Wall Splitting

*Rank estimated based on test results for other specimens.

3.4.1 Strength of Grout

Grout strength ranging from about 2700 psi to 6800 psi (18.6 MPa to 46.9 MPa) had a significant effect on joint strength. Measured ultimate loads versus grout strengths for test specimens are shown in Fig. 16. It can be seen that joint strength generally increased with grout strength, provided the capacity was controlled by grout crushing. However, as indicated in Table 5, for joint configuration JC10, high strength grout alone did not ensure greater joint capacity. As shown in Fig. 16 for Specimen B-4, joint strength was controlled by wall splitting, and grout strength was never reached.

3.4.2 Transverse Wall Reinforcement

Split resisting reinforcement had no effect on strength in joint configurations JC1 through JC4. In these configurations, joint strengths were controlled by grout crushing. This is shown in the first four joint configurations of Table 5. Reinforcement increased the capacity when the strength was controlled by wall splitting in an unreinforced wall. This corresponds to joint configurations JC6 and JC9 and was observed in Specimens J-2 and J-3.

3.4.3 Filled Slab Cores

For similar conditions of grout strength and wall reinforcement, the filled cores in the connection region increased joint capacity. Filled cores increased the stiffness of the slab ends thereby contributing to a more uniform vertical stress distribution in the joint. Consequently, crushing of the grout occurred at higher loads.

3.4.4 Applied Floor Moment and Rotation

Several loading conditions were used to determine the influence of moment and rotation on joint strength. The intensity of concentrated floor load was such that the negative moment introduced at

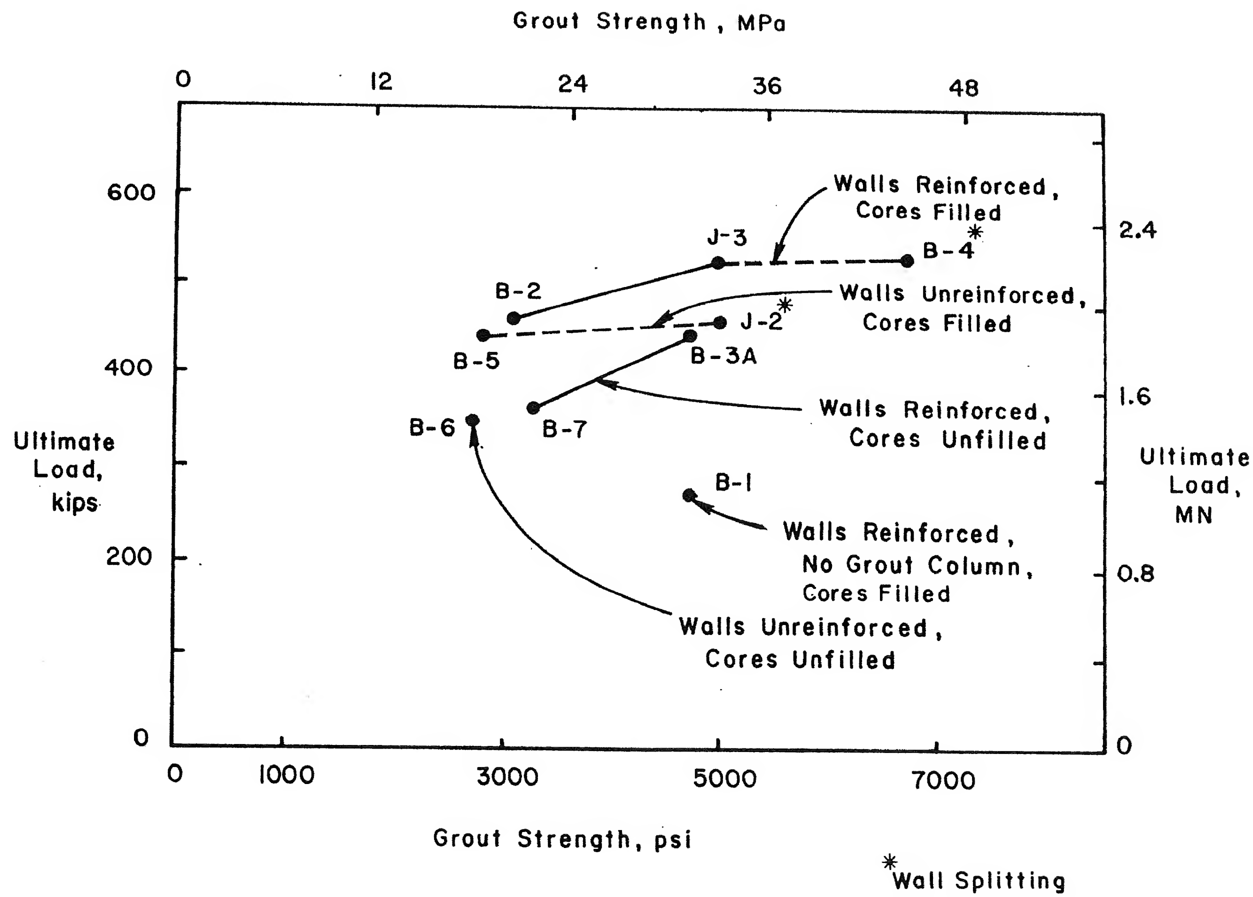


Fig. 16 Interior Joint Strengths, All Series

the joint was slightly less than the calculated cracking moment. The load was positioned on the slab to provide a moment to shear ratio of about 5 at the joint. The results indicate that floor moment and rotation do not affect joint strength significantly. Rotation does induce some tensile splitting forces into the upper wall. However, the effect is minimal and generally can be neglected.

3.4.5 Dry Packing

In addition to the variables discussed above, joint performance was influenced significantly by the uniformity of dry-packed mortar below the upper wall panel. Well-packed mortar lead to uniform stresses below the upper wall. Poor dry packing lead to nonuniform stresses, thereby substantially reducing joint strength due to premature splitting of the upper wall.

3.5 Experimental Determination of "Stiffness Factor"

Vertical compressive load applied to the upper wall panel is transferred to the lower wall panel through the grout column between the floor slabs and the slabs supported on the bearing pads. A greater part of the load transfer, however, takes place through the grout column. The percentage of load transferred through different elements in a horizontal joint is a function of the relative stiffness of each element in relation to the total stiffness of the connection. Stress flow in the slabs is nonuniform both across the slab depth and in the direction of the floor span. Therefore, the effective plank stiffness is indeterminate and varies with material properties, load pattern, and geometry of connection. Load transfer is considered based on measurements made on joint shortening and grout column shortening.

3.5.1 Joint Shortening

Joint shortening was measured over a height of about 10.62 in. (270 mm). This distance included grout column, dry pack, and about 3/4 in. (19 mm) each of top and bottom walls.

The following analysis is based on the assumption of a uniform stress throughout the idealized vertical column comprised of four different elements as shown in Fig. 17(a). This idealized column closely represents conditions in the joint after vertical cracking takes place at the end of each floor element separating the grout column from the grout in the slab cores. Each discrete column is considered to act independently.

Using the notation given in Fig. 17(a),

$$\sigma = \frac{\delta\ell_1}{\ell_1} E_1 = \frac{\delta\ell_2}{\ell_2} E_2 = \frac{\delta\ell_3}{\ell_3} E_3 = \frac{\delta\ell_4}{\ell_4} E_4 \qquad \text{(Eq. B-1)}$$

$$\begin{aligned} \delta\ell_3 &= \delta\ell - \delta\ell_1 - \delta\ell_2 - \delta\ell_4 \\ &= \delta\ell - \sigma\left(\frac{\ell_1}{E_1} + \frac{\ell_2}{E_2} + \frac{\ell_4}{E_4}\right) \qquad \text{(Eq. B-2)} \end{aligned}$$

where σ = uniform vertical stress in column,

$\delta\ell_1$, $\delta\ell_2$, $\delta\ell_3$, $\delta\ell_4$ = shortening over heights ℓ_1, ℓ_2, ℓ_3, ℓ_4 of Elements 1, 2, 3, 4, respectively,

$\delta\ell$ = measured joint shortening = $\delta\ell_1 + \delta\ell_2 + \delta\ell_3 + \delta\ell_4$, and

E_1, E_2, E_3, E_4 = modulus of elasticity of Elements 1, 2, 3, 4, respectively.

The shortening in grout column, $\delta\ell_3$, was determined from the above expression by assuming a uniform vertical stress, σ, and using the corresponding values of E_1, E_2 and E_4 from a family of stress-strain curves plotted for materials of different compressive strengths. A trial and error method was used to match the assumed vertical stress with the grout column stress corresponding to calculated grout column shortening $\delta\ell_3$.

Therefore, the amount of load transferred through the grout column, P_g, is given by:

$$P_g = \frac{\delta\ell_3}{\ell_3} (E_3)(A_g) \qquad \text{(Eq. B-3)}$$

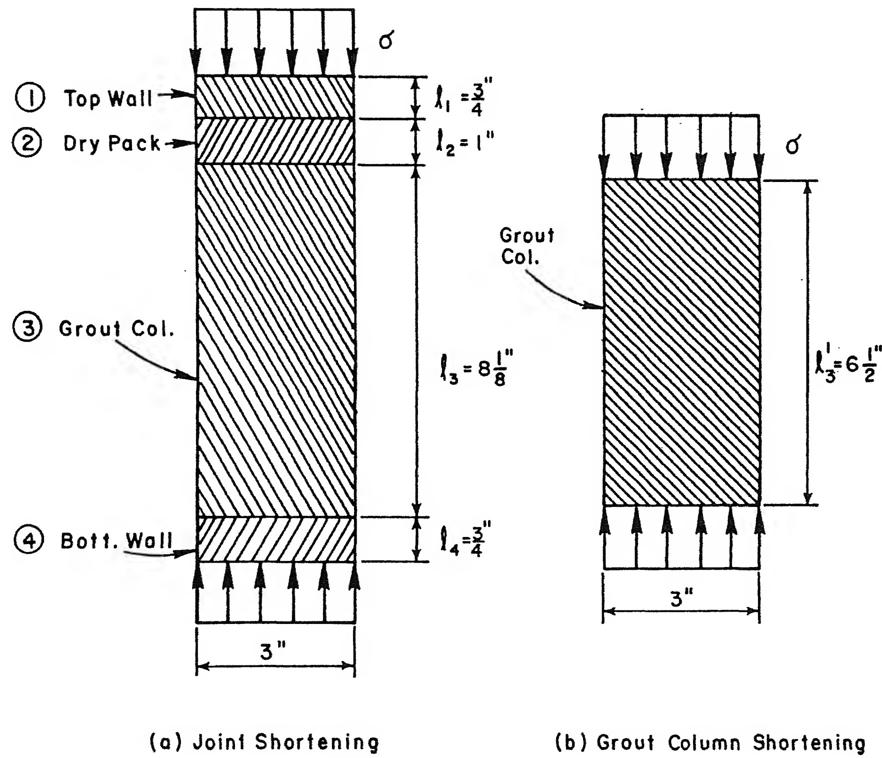


Fig. 17 Idealized Uniform Stress Region in a Horizontal Joint

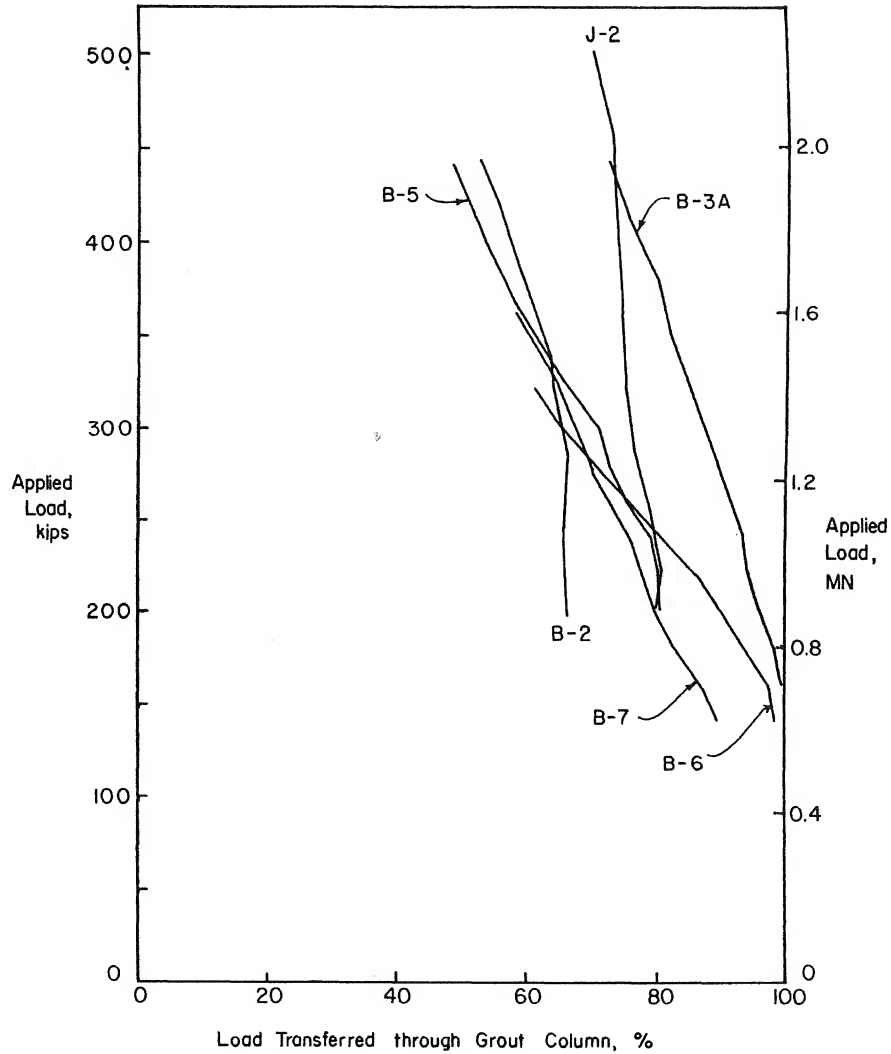


Fig. 18 Applied Load versus Load through Grout Column

$$\sigma = \frac{P_g}{A_g} \qquad \text{(Eq. B-4)}$$

where A_g = cross-sectional area of grout column

3.5.2 Grout Column Shortening

Stress analysis based on total joint shortening described in Section 3.5.1 was quite complex. It involved materials with different elastic properties. The voids left between different materials as a result of construction procedures and subsequent shrinkage were not considered in the analysis. This resulted in a high calculated percentage of load transferred through the grout column in the initial load stages.

Shortening in the grout column alone was also measured in Specimens B-6 and B-7. Strain measurements were taken over a height of about 6.3 in. (160 mm).

Assuming a uniform stress throughout the length of the grout column as shown in Fig. 17(b), the percentage of applied load transferred through the grout column was calculated.

$$\sigma = \frac{\delta \ell'_3}{\ell'_3} E_3 \qquad \text{(Eq. B-5)}$$

where $\delta \ell'_3$ = shortening over height ℓ'_3 of grout column

Therefore, the amount of load transferred through the grout column is given by:

$$P_g = \frac{\delta \ell'_3}{\ell'_3} (E_3) (A_g) \qquad \text{(Eq. B-6)}$$

Using the procedure described in Sections 3.5.1 and 3.5.2, the percentage of load transferred through the grout column was calculated

for different test specimens. These data are plotted in Fig. 18. Values are not included for loads prior to formation of the idealized column by cracking at the slab end and grout column interface. Results for Specimens J-3 and B-4 are not plotted because of inconsistent data. Figure 18 shows that the percentage of load transferred through the grout column decreased as the load was increased.

4. TEST RESULTS - EXTERIOR JOINTS

4.1 Specimen Strength

Ultimate test loads are given in Table 6. For convenience, these results are expressed both as ultimate load, P_u, and as average wall stress. The latter was obtained by dividing the ultimate load by the bearing area of the wall panel. Also given in Table 6 are the observations at ultimate load indicating that crushing of the grout occurred in all specimens.

4.2 General Behavior

As in interior joints, vertical load can pass through an exterior joint in either of two fashions. In the case shown schematically in Fig. 19(a), the joint functions in a monolithic manner. Load is distributed across the top, nonuniformly due to the built-in eccentricity of the joint. At the bottom of the joint, load is funnelled into the grout column due to the soft bearing pads beneath the ends of the slabs.

In the case shown in Fig. 19(b), the joint consists of two discrete vertical "columns": a grout column in the center and a column on one side consisting of the end of the slab. The load that each "column" supports varies with the total stiffness of that column and the eccentricities present within the exterior joint. As there exists a significant built-in eccentricity because of the discrete slab end on only one side, uniform material properties will not produce uniform stresses across the joint, as in the case of interior joints.

For a particular exterior joint, both load flow patterns and behavior are governed by the same four variables as interior joints described in Section 3.3. However, in exterior joints the effects are much less pronounced. As noted above, the basic configuration of the joint leads to nonuniform stresses no matter what the material properties may be. As shown schematically in Fig. 19(c), the joint initially tends to transfer most of the load to the centrally located grout column. Consequently,

TABLE 6 - TEST RESULTS-EXTERIOR JOINTS

Specimen Number	Ultimate Load P_u (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
E-1	300	1560	5420	2980	Filled	Grout Crushing	--
E-2	290	1510	5180	2840	Unfilled	Grout Crushing	--
E-3	280***	1460	5180	4770	Unfilled	Grout Crushing	Poor Dry Packing (inadequately packed)
E-4	380	1980	4900	4630	Filled	Grout Crushing	--
E-5*	400	2080	4900	4510	Filled	Grout Crushing	--

*Wall Panels reinforced with 6x6 - W 2.9 X W 2.9, $A_s = 0.116$ in.^{2}

**Average wall stress obtained by dividing the ultimate load by the bearing area of wall panel (bearing area is 24x8 in.)

***Reduced joint capacity due to poor dry packing

Metric Equivalents: 1 psi = 6.89 kPa
1 in. = 25.4 mm
1 kip = 4.448 kN

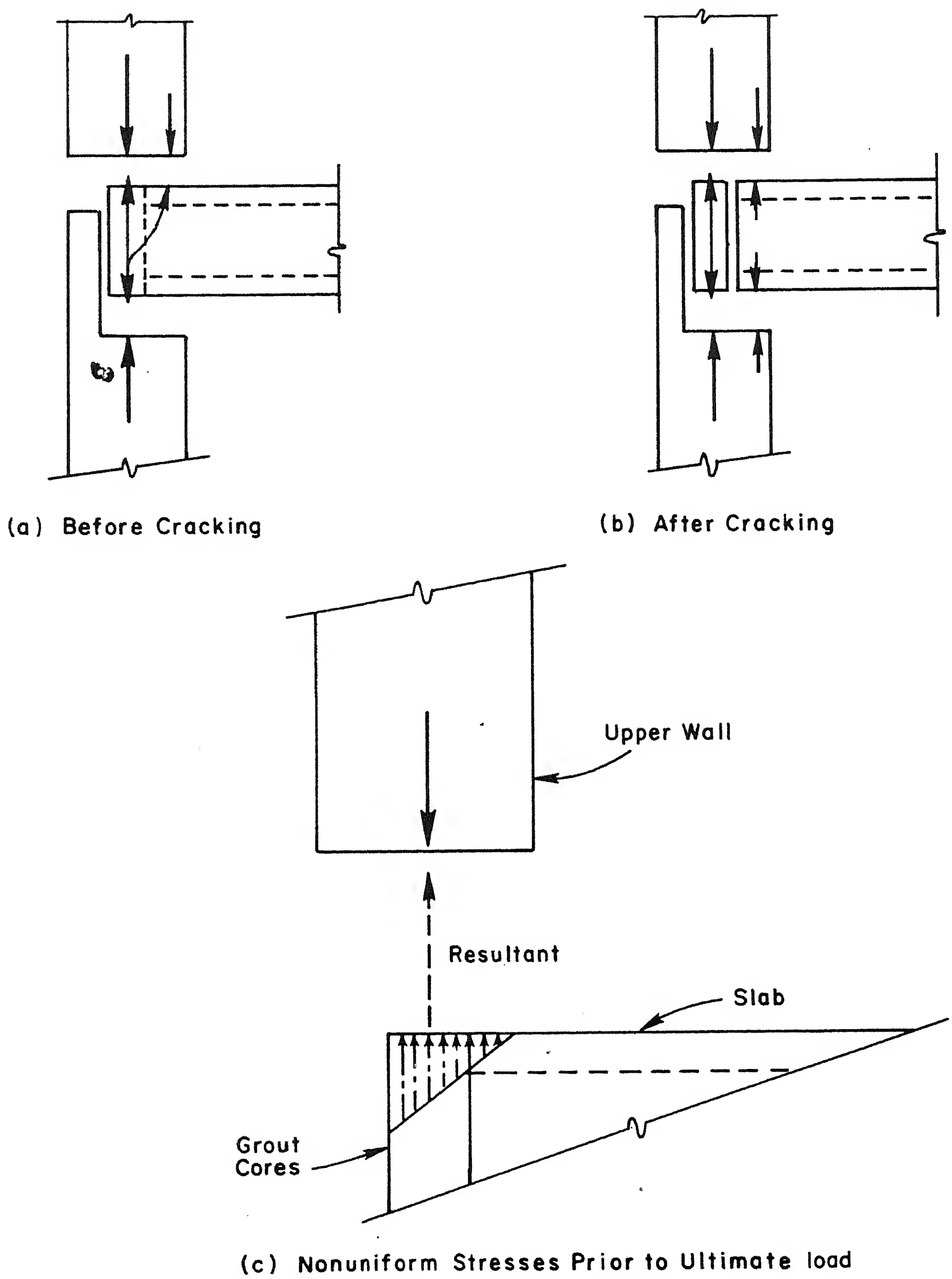


Fig. 19 General Behavior - Exterior Joints

in all cases, the percentage of applied load transferred through the grout column to the lower wall is substantially higher in exterior joints when compared to similar interior joints.

4.2.1 Case 1: Low and Medium Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

For Case 1, shown in Fig. 20(a), load flow is through discrete vertical columns when cores are unfilled, and through a monolithic element when cores are filled. In the latter cases, however, the grout carries most of the load. As load is increased, the grout is crushed before tensile splitting stresses, caused by the vertical stress concentration, become critical in the wall panel. This is identified as Stage 1.

With the loss of the grout column, load is transferred to the slab ends, which also crush, identified as Stage 2. Since the capacity of the grout column is greater than that of the slab end, maximum load is reached at Stage 1.

Stresses in the wall panel never become critical. Therefore, the behavior and capacity of this joint configuration are not altered by reinforcing. A specimen exhibiting this behavior is shown in Fig. 21. Similar behavior was observed in all specimens at ultimate load.

4.2.2 Case 2: High Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

No specimens representing Case 2, shown in Fig. 20(b), were tested. The load flow is similar to that of Case 1. Due to the eccentric bearing of the wall and to the soft bearing pads beneath the slab ends, the grout again transfers most of the load. The grout has a higher strength than the wall concrete. Consequently, it is expected that horizontal tensile stresses in the walls, due to the vertical stress concentration, would become critical long before the grout column capacity is reached.

(a) Low & Medium Strength Grout Cores Filled or Unfilled, Walls Reinforced or Unreinforced

(b) High Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

Load Stage	(a)	(b)
	*1 - Grout Crushes	1 - Both Walls Crack
	2 - Slab Ends Crush	*2 - Both Walls Split

*Ultimate Capacity

Fig. 20 Behavior at Successive Load Stages - Exterior Joints

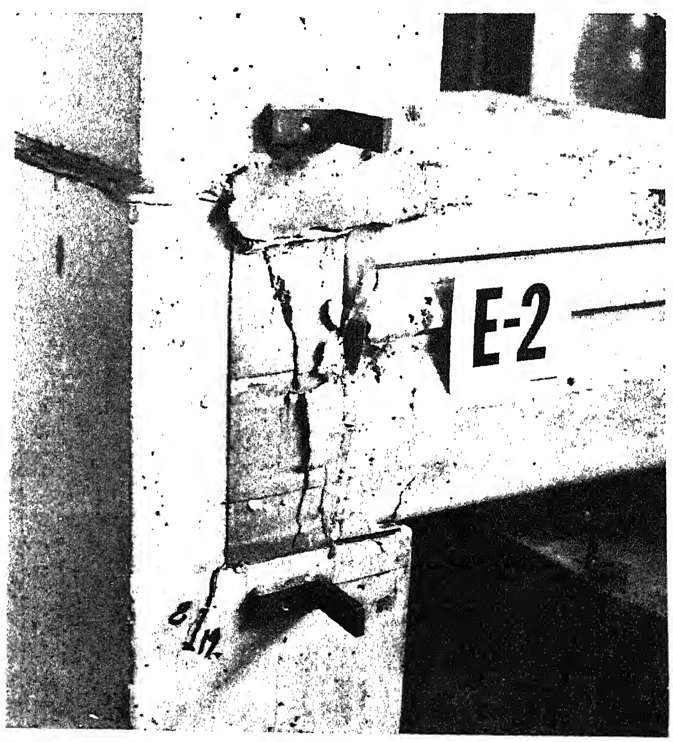


Fig. 21 Damage Pattern at Ultimate Load - Exterior Joints

Increased load would first crack the upper and lower walls, and then split them. This is identified as Stages 1 and 2, respectively. Splitting would likely occur whether or not the walls were nominally reinforced.

4.3 Effects of Variables on Joint Strength

Grout strength was the only variable in the test program that influenced strength of the joint. This occurred because the basic configuration of the joint caused most of the load to be transferred through the grout column.

Based on the variables examined, a list of exterior joint details is given in Table 7. The table lists joint configurations in ascending order of capacity. Behavior of the last two joint configurations JC13 and JC14 have been estimated.

4.3.1 Strength of Grout

Grout strength ranging from approximately 2800 psi to 4800 psi (19.3 MPa to 33.1 MPa) had a significant effect on joint strength. Measured ultimate loads versus grout strength are shown in Fig. 22. It can be seen that with the exception of Specimen E-3, which was poorly dry packed, joint strength increased with grout strength.

As suggested in Table 7 for configuration JC13 and JC14, the capacity of joints with high strength grout is expected to be controlled by wall splitting.

4.3.2 Transverse Wall Reinforcement

Addition of split-resisting reinforcement has no effect on joints with low or medium strength grout. Reinforcement will increase joint capacity only when the mode of behavior at ultimate is wall splitting in a non-reinforced wall. Joint configurations JC13 and JC14 would be expected to perform this way.

TABLE 7 - EXTERIOR JOINT CONFIGURATION IN ASCENDING ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
E-1,E-2	JC11	Low	Either	Either	1	Grout Crushing
E-3,E-4,E-5	JC12	Medium	Either	Either	1	Grout Crushing
--	JC13*	High	Either	No	2	Wall Splitting
--	JC14*	High	Either	Yes	2	Wall Splitting

*Rank estimated based on test results for other specimens.

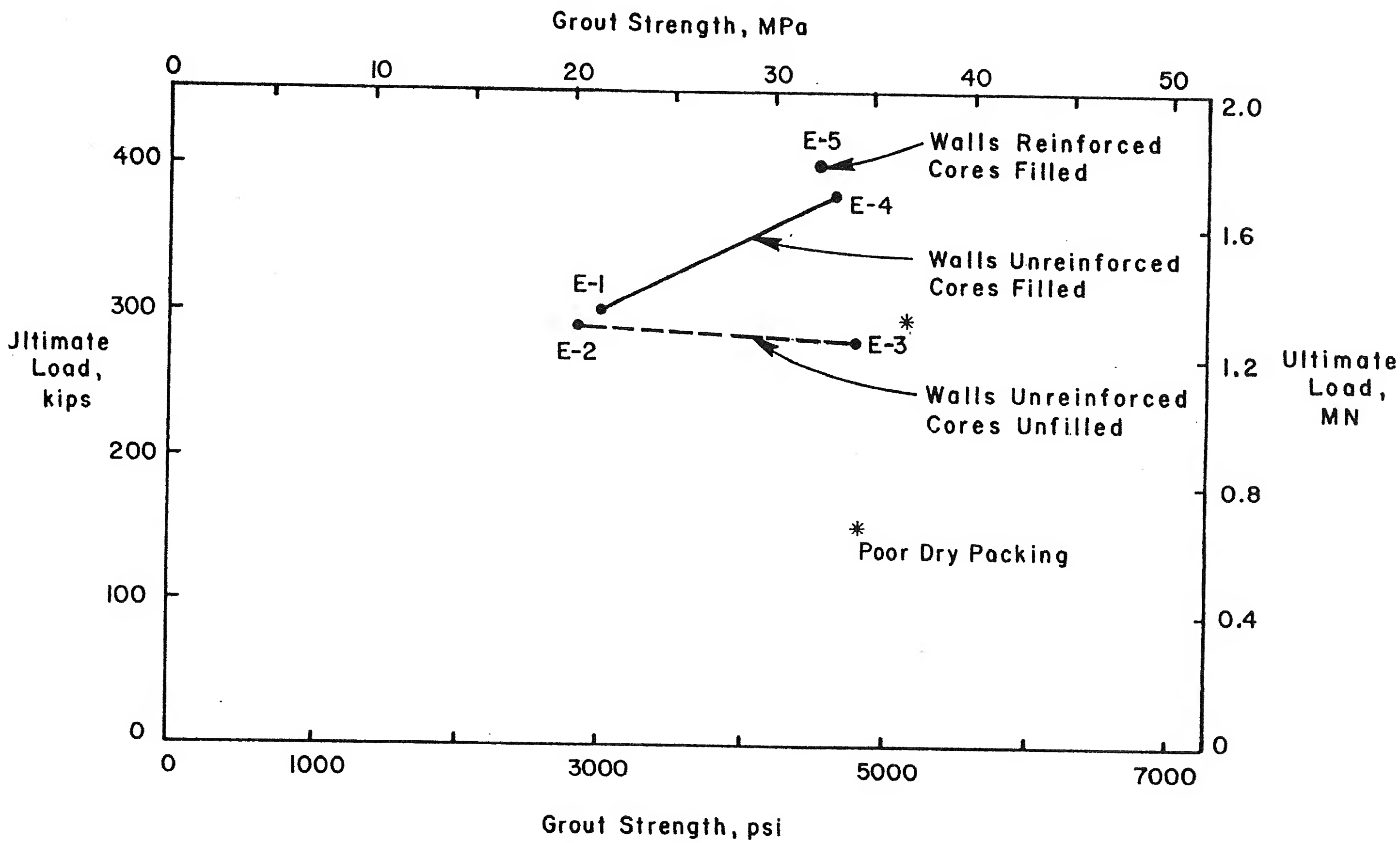


Fig. 22 Exterior Joint Strengths - All Specimens

4.3.3 Filled Slab Cores

Filling the cores in the connection region increases the joint capacity. As the exterior joints have a slab on one side of the joint only, lesser load is transferred through the slab end as compared to the interior joints. Therefore, filling the cores in exterior joints will have somewhat less of an effect.

4.3.4 Dry Packing

Poor dry packing can lead to premature joint failure. Dry packing is more difficult in exterior joints, because mortar has to be packed from one side of the joint only. Consequently, the probability of inadequate packing is higher.

5. DESIGN PROCEDURES

5.1 Prestressed Concrete Institute Methods

In recent years, several methods to determine the load capacity of horizontal connections in large panel structures have been proposed. This section discusses three design procedures proposed by the Prestressed Concrete Institute (PCI)[5].

Prestressed Concrete Institute Method 1[5] is based on strengths of joint components. Applied design load on the joint is distributed to the components of the joint according to the stress-deformation and strength characteristics of the components. It also allows a "confinement factor" on the cylinder strength of concrete or grout in the joint.

This method is empirical in nature, and is complex to use. There are few experimental data to verify the stress-strain relationships used in the analysis. Elastic properties of the bearing pads used in the experimental tests described in this report differed substantially from the values suggested in PCI Method 1.

Prestressed Concrete Institute Method 2[5] is based on elastic analysis of a joint. With this approach, the joint is divided into a series of discrete vertical "columns." The amount of load that each "column" supports is a function of the stiffness of that particular column. The method permits determination of the stress distribution on components of the joint under service load conditions. However, Method 2 has the following limitations:

1. It underestimates the effective stiffness of a slab by limiting the width of the "slab column" to the bearing length of the floor slab in calculating areas of discrete vertical "columns." However, a
that additional plank l
participates in transfe

the lower wall. This extra length alters the calculated load distribution.

2. It does not consider the use of hollow-core slabs and the additional stiffness provided by the grout in the slab cores within the connection region.

3. It permits determination of stresses in the elastic range, but not the load capacity of a joint. Also, the method does not consider the effect of wall reinforcement or the possibility of a splitting failure when high strength grout is used.

Prestressed Concrete Institute Method 3[5], is based mainly on tests conducted by the Danish Structural Research Center. Their empirical expression seems valid, but is applicable only if grout strengths within the joint and the wall concrete strength are similar.

5.2 Proposed Design Procedures

5.2.1 Interior Joints

Vertical compressive load applied to the upper wall is transferred to the lower wall through the grout column and the floor slab ends. A greater part of the load is carried by the grout column and slabs carry the rest. Ultimate load, P_u, can be separated into two parts as follows:

$$P_u = P_g + P_s$$

where P_u = joint strength

P_g = amount of load transferred through the grout column

P_s = amount of load transferred through the floor slabs

The amount of load transferred through slabs can be increased if cores are filled. It should be noted, however, that, P_s, does not represent the load capacity of an ungrouted connection. It is

the amount of load carried by the slabs when joint reaches ultimate capacity. Joint capacity is reached when grout in the joint is crushed. Strength of an ungrouted connection will, usually, be much higher than P_s. This strength can be determined directly from the bearing area of slab ends and the compressive strength of floor slab concrete.

The proposed method limits the maximum useable grout strength, f_u, and thus, ensures that joint capacity is controlled by grout crushing rather than wall splitting. The maximum useable grout strength, and consequently joint capacity can, however, be increased by selecting proper joint variables, such as grout and wall strengths, wall reinforcement, and by filling the slab cores. Therefore, high strength grout can only be used effectively if the walls use high strength concrete, they are reinforced against splitting, and the slab cores are filled with grout.

Based on the maximum useable grout strength, f_u, the following expression for capacity of interior horizontal joints was developed:

$$P_g = K\,P_u$$

$$P_s = (1 - K)P_u$$

From basic principles,

$$P_g = t\,L\,f_u$$

where t = width of the grout column - in this case 3 in. (76 mm),

L = horizontal length of grout column,

f_u = maximum useable strength of grout defined as follows: compressive strength of grout, f_g, or wall concrete, f'_c, whichever is less, but not more than 4000 psi (27.6 MPa), unless the walls are reinforced against splitting and slab cores are filled with grout,

f_g = compressive strength of grout in the joint, and

K = factor representing the percentage of ultimate load transferred through the grout column. K was found to increase linearly from a minimum value of 0.65 for a grout strength of 2500 psi (17.24 MPa) to a value depending on strength of grout in the joint, f_g.

For simplicity, K can be taken as follows:

$$K = 0.65 + \left[\frac{f_g - 2500}{50{,}000}\right] \quad \text{for } f_g \text{ in psi, or}$$

$$= 0.65 + \left[\frac{f_g/0.0069 - 2500}{50{,}000}\right] \quad \text{for } f_g \text{ in MPa}$$

Therefore, $P_u = P_g/K$

The filled core factor, C, can be used to account for added joint strength due to increased slab stiffness. The filled core factor is inversely proportional to the square root of grout compressive strength, f_g.

Therefore, $$P_u = \frac{t\ L}{K} f_u\ C \qquad \text{(Eq. B-7)}$$

where C = filled core factor determined as follows:

For filled slab cores:

$$C = 1.4\sqrt{\frac{2500}{f_g}} \quad \text{for } f_g \text{ in psi, or}$$

$$= 1.4\sqrt{\frac{2500}{f_g/0.0069}} \quad \text{for } f_g \text{ in MPa,}$$

but not less than 1.0

For unfilled slabs cores:

C = 1.0

It should be noted that the above expression is based on tests applied to only one type of joint configuration. It may not be applicable to other types of joints with different geometry or material properties. However, the configuration used in this investigation is representative of horizontal joints used in large panel structures.

5.2.2 Exterior Joints

It appears from the tests that for exterior joints, most of the load applied to the upper wall panel is transferred to the lower wall panel through the grout column. Stiffness provided by the slab may, therefore, be ignored.

Therefore, $P_u = P_g$

Based on the experimental study on exterior joints, the following expression is proposed for determining a conservative value for the joint strength:

$$P_u = t\, L\, f_u\, C \qquad \text{(Eq. B-8)}$$

where

P_u = joint strength,

t = width of grout column - in this case 3 in. (76 mm),

L = horizontal length of grout column,

f_u = maximum useable strength of grout defined as follows: compressive strength of grout, f_g, or wall concrete, f'_c, whichever is less, but not more than 4000 psi (27.6 MPa), unless slab cores are filled with grout,

f_g = compressive strength of grout in the joint, and

C = filled core factor determined as follows.

For filled slab cores:

$$C = 1.2\sqrt{\frac{2500}{f_g}} \quad \text{for } f_g \text{ in psi, or}$$

$$= 1.2 \sqrt{\frac{2500}{f_g/0.0069}} \quad \text{for } f_g \text{ in MPa,}$$

but not less than 1.0

For unfilled slab cores:

$$C = 1.0$$

It should be noted that the above expression is based on limited number of tests applied to one type of joint configuration. It may not be applicable to other types of joints with different geometrical or material properties. However, the configuration used in this investigation is representative of horizontal joints commonly used in large panel structures.

5.3 Comparison of Measured and Calculated Strengths

Strengths for the interior joint specimens were calculated from the three PCI Methods and from the proposed design expression. These were compared with the measured strengths. The values are listed in Table 8.

Prestressed Concrete Institute Method 1 is based on stress-deformation characteristics of the joint components. An increase in grout stress is allowed due to its confined nature in the joint. However, the method does not distinguish between slab cores filled and unfilled. The maximum value of confinement factor is arbitrarily fixed at 2.0. In calculating the load capacities using this method, confinement factors of 2.0 and 1.0 were assumed for slab cores filled and unfilled, respectively. Furthermore, there is no provision for additional joint strength due to reinforced wall panels, or loss of strength due to wall splitting prior to grout crushing in unreinforced wall panels. Consequently, the calculated strengths of Specimens J-2, J-3 and B-4 were substantially different from measured strengths.

Prestressed Concrete Institute Method 2 gives stress distribution under service load conditions only. In calculating the load capacity of joints

TABLE 8 - COMPARISON OF MEASURED AND CALCULATED STRENGTHS - INTERIOR JOINTS

Specimen Number*	Calculated Load Capacity ** (kips)				Measured Strength (kips)
	PCI Methods			Proposed Method	
	1	2	3		
B-6	211	286	252	300	343
B-7	249	332	299	351	360
B-5	460	309	275	417	440
B-2	502	334	301	433	460
B-3A	344	445	417	417	440
J-2	761	488	462	411	465
J-3	761	488	462	496	520
B-4	1028	642	628	519	525

*Trial Specimens JM-1 and J-1 have been omitted because their failure was due to poor dry packing. Specimen B-1 has been excluded because there was no grout column provided.

**See Table 2 for strength of grout, concrete and other variables.

Metric equivalent: 1 kip = 4.448 kN

from this method, the stress or load distribution at ultimate was assumed to be the same as at service load. Also, since this method does not take into account the effect of splitting in the walls, calculated strengths of Specimens J-2 and B-4 are overestimated. These specimens contained high strength grout. Wall splitting occurred before the grout crushed. There is no provision for added joint strength due to filled slab cores. Therefore, calculated strengths of Specimens B-2 and B-5 are underestimated.

Prestressed Concrete Institute Method 3 is applicable only when grout and wall strengths are approximately equal. For the present tests, this

corresponds to the medium strength grouts. Good agreement was obtained between measured and calculated strengths for Specimens B-3A and J-2. However, strength of Specimen J-3 with reinforced wall panels, was underestimated. Values for grouts with lower and higher strengths are also given in Table 8 for comparison. In these specimens, agreement between calculated and measured strengths is poor.

Out of all the methods proposed prior to the present research, PCI Method 2, based on elastic analysis of a joint provided the most reasonable approach for designing interior wall-to-floor connections. However, as described earlier in this section, this method gives stress distribution in the elastic range only, and it does not consider the cases where joint capacity is limited by wall splitting. Consequently, the use of this method for predicting joint strength is very limited.

The proposed design method described in Section 5.2 is based on the present experimental investigation. It predicts the joint capacity taking into account all modes of joint behavior both under service and inelastic loading conditions. As shown in Table 8, the load capacity calculated by the proposed method agrees very favorably with the measured joint strengths.

Capacities for exterior joint specimens were also calculated from the proposed design expression. A comparison with measured values is given in Table 9.

TABLE 9 - COMPARISON OF MEASURED AND CALCULATED STRENGTHS - EXTERIOR JOINTS

Specimen Number*	Joint Strength** (kips)	
	Calculated by Proposed Method	Measured
E-1	236	300
E-2	204	290
E-3	288	280*
E-4	333	380
E-5	325	400

*Specimen E-3 has reduced joint capacity due to poor dry packing.

**See Table 3 for strength of grout, concrete and other variables.

Metric equivalent: 1 kip = 4.448 kN

6. CONCLUSIONS

The following conclusions are based on results of this experimental program.

6.1 Interior Joints

1. Joint capacity increases with grout compressive strength, when joint strength is controlled by grout crushing. This applies when the grout strength is less than about 80% of the wall concrete compressive strength.

2. Wall Splitting is not a problem when low-strength grout is used. However, for unreinforced walls, when the grout compressive strength exceeds about 80% of wall concrete compressive strength, wall splitting occurs prior to grout reaching its strength. When the walls are adequately reinforced, development of full grout strength results in increased joint capacity. The amount of wall reinforcement required to limit splitting increases with grout compressive strength.

3. Filling slab cores with grout directly affects the joint strength. For low-strength grouts, joint strength increases substantially with filled cores. With medium strength grout, behavior at ultimate load changes from grout crushing to wall splitting when slab cores are filled. With both medium and high strength grouts, wall reinforcement limits splitting and thus, the benefits from filling the cores are utilized.

4. The quality of dry pack below the upper wall panel has a significant effect on the joint strength. Inadequate dry packing with voids leads to a substantial loss of joint capacity.

5. Floor moment and rotation do not have a significant effect on the strength of a wall-to-floor connection.

6. The joint capacities calculated by the proposed expression (Eg. B-7) agree very closely with the measured joint strengths.

6.2 Exterior Joints

1. When grout strength is equal to or less than wall concrete compressive strength, joint capacity increases with grout compressive strength.

2. Filled slab cores in exterior joints minimize the effect of built-in or accidental eccentricity. Joint strength, however, is not significantly improved.

3. When grout strength is less than or equal to wall concrete compressive strength, wall splitting does not occur.

4. When the grout strength is greater than the wall strength, it is anticipated that wall splitting will occur unless the walls are adequately reinforced.

5. The proposed expression (Eq. B-8) gives conservative values of load capacities for exterior horizontal joints when compared with the measured strengths.

Detailed recommendations for specific analysis techniques and design criteria are given in Report 5[2].

APPENDIX A - NOTATIONS

A_g = cross-sectional area of grout column

C = confinement factor

E_1 = modulus of elasticity of upper wall panel

E_2 = modulus of elasticity of dry pack

E_3 = modulus of elasticity of grout in the joint

E_4 = modulus of elasticity of lower wall panel

f'_c = compressive strength of concrete

f_g = compressive strength of grout in the joint

f_u = maximum useable strength of grout for calculating joint strength

F.M. = fineness modulus

K = stiffness factor

L = horizontal length of grout column

$\delta\ell_1$ = shortening measured over a height ℓ_1 at the lower end of upper wall panel (See Fig. 17)

$\delta\ell_2$ = shortening measured in dry pack, total height = ℓ_2 (See Fig. 17)

$\delta\ell_3$ = shortening measured in grout column, total height = ℓ_3 (See Fig. 17)

$\delta\ell_4$ = shortening measured over a height ℓ_4 at the upper end of lower wall panel (See Fig. 17)

$\delta\ell'_3$ = shortening measured in grout column over a height ℓ'_3 (See Fig. 17)

$\delta\ell$ = $\delta\ell_1 + \delta\ell_2 + \delta\ell_3 + \delta\ell_4$ = total joint shortening measured over a height $\ell = \ell_1 + \ell_2 + \ell_3 + \ell_4$ (See Fig. 17)

LP = large panel

P_g = vertical load transferred through grout column

P_u = joint strength

t = thickness of grout column

σ = vertical stress in grout column

APPENDIX B - GLOSSARY OF TERMS

Accidental eccentricity:	An eccentricity which exists as a direct result of errors in either the manufacturing or erection process.
Assembly:	An aggregate of panels.
Bearing area:	Area of the wall panel through which vertical compressive force is applied to the joint; 24 x 8 in. (610 x 203 mm) in this case.
Built-in eccentricity:	An eccentricity which exists as a result of exterior joint configuration.
Connections:	A position or region where two or more building components, panels or assemblies are put together or united.
Connection stiffness: (for vertical loads)	The sum of stiffnesses of grout and plank end "columns" composing a connection.
Confinement factor:	A factor used to allow for increased compressive strength of grout, reflecting the confined nature of material in the joint.
Continuity:	The capacity for load transfer between two or more elements where load is axial, shear, moment, or any combination thereof.
Damage pattern:	Mode of behavior at ultimate load.
Deformation:	A change in dimension or shape.

Dry pack:	To forcibly ram a moist portland cement aggregate mixture (mortar) into a confined area; also, the mixture so placed.
Dry-packed mortar:	A mortar mixture sufficiently dry to be consolidated by heavy ramming.
Ductility:	The measure of a structural component's (element or joint) ability to sustain inelastic deformations, i.e. the ratio of the maximum deformation to the yield deformation.
Exterior joints:	Horizontal joints connecting exterior wall panels and floors.
Filled slab cores:	Hollow cores of precast concrete planks filled with fluid grout (extending about 3-1/2 in. (89 mm) into the cores).
Floor moment and rotation:	Moment applied to simulate actual loading conditions (less than calculated cracking moment).
Floor panel:	Horizontal precast concrete element, typically consisting of hollow core precast concrete planks.
Floor plank:	A horizontal precast concret element, typically extruded and reinforced with high-strength steel. Also known as hollow core or hollow-core slab.
Grout:	Mixture of cementitious material and aggregate to which sufficient water is added to produce pouring consistency without segregation of the constituents.

Grouting:	The process of filling with grout.
Grout stiffness ratio:	Ratio of grout column to the total connection stiffness; also defined as stiffness factor.
Grout strength:	Average compressive strength of grout measured on six 6x12-in. (152x305 mm) cylinders. Ranges of strength are: Low: 2500 to 4000 psi (17.2 to 27.6 MPa) Medium: 4000 to 5500 psi (27.6 to 37.9 MPa) High: 5500 to 7000 psi (37.9 to 48.3 MPa)
Horizontal joint:	The zone common to the wall and floor panels in a horizontal direction.
Integrity of connection:	The ability of a connection to transfer loads from one portion or element to another while retaining its structural stability.
Interior joints:	Horizontal joints connecting interior wall panels and floors.
Joint strength:	The maximum load sustained by a joint.
Large panel (LP) structures:	A structural system composed of vertical load-carrying elements of large precast wall panels with precast floors and roofs of panels or planks.
Optimum wall reinforcement:	Minimum transverse reinforcement provided at the ends of wall panels to keep the walls from splitting before grout is crushed in the joint.
Service load:	Unfactored normal loading condition.

Stiffness factor: See grout stiffness ratio.

Strength of grout: See grout strength.

Transverse wall reinforcement: Optimum amount of reinforcement provided at the end of wall panels to limit splitting.

Ultimate joint load: See joint strength.

Ultimate load: (general) The maximum load which may be placed on a connection, member or a structure before its failure; also, the load at which a connection unit or structure fails.

Wall panel: A vertical precast concrete element either load-bearing or non-load-bearing; usually one-story in height, with lengths typically ranging from 10' to 45'.

Wall reinforcement: See transverse wall reinforcement.

APPENDIX C - DETAILS OF EXPERIMENTAL PROGRAM

C.1 Assembly of Specimens

A test specimen consisted of precast top and bottom wall panels, and prestressed concrete hollow-core slabs assembled as shown in Figs. 3 and 4.

To assemble a specimen, the lower wall block was plastered to the floor, and the hollow-core planks were lowered into position on top of it. The ends of the slabs were supported on 2-in. (51 mm) wide elastic bearing pads on both sides of the joint. The other ends of floor slabs were temporarily supported on screw jacks placed on concrete blocks as shown in Figs. 7 and 8. Prior to testing, the screw jacks were replaced with load cells.

In a complete joint test, the grout in the joint extended about 3-1/2 in. (89 mm) into the slab cores to provide continuity. This was accomplished by inserting crumpled newspapers as "dams" to stop the flow of grout beyond a desired point. In tests where the slab cores were deliberately left unfilled, the cores were completely blocked at the face using duct tape. The joint was then filled with grout.

The wall panel above the joint rested on dry-packed mortar about 1-in. (25.4 mm) thick. The mortar was packed from both sides of the wall to completely fill the joint.

C.2 Materials and Fabrication

C.2.1 Floor Elements

Hollow-core slabs used in all series had a design compressive strength of 5000 psi (34.5 MPa). Cross-sectional dimensions are shown in Fig. 23.

C.2.2 Wall Panels

Precast concrete wall panels were used. Top and bottom wall blocks were identical. A cross section is shown in Fig. 24.

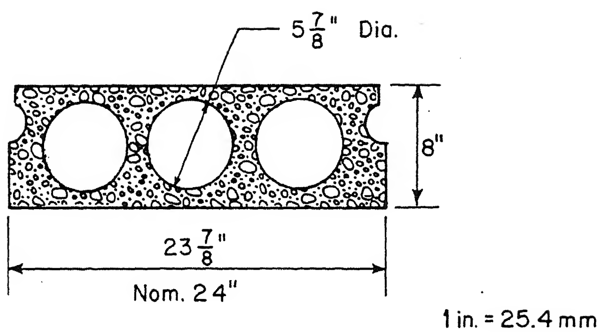


Fig. 23 Slab Cross Section

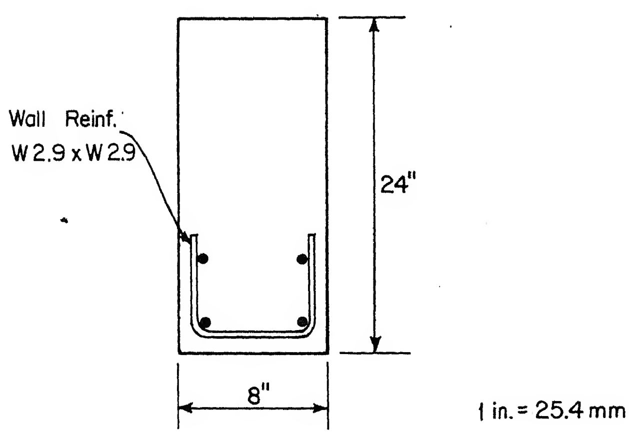


Fig. 24 Wall Cross Section

A concrete mix designed to yield a cylinder compressive strength of 5000 psi (34.5 MPa) at approximately 14 days was used. The concrete was made using Type I Portland Cement, Elgin Sand and Gravel with a maximum aggregate size of 3/4 in. (19 mm). The specimens and test cylinders were cured in the forms under plastic sheets for at least 3 days after casting. Compressive strength of concrete was determined from the average of nine 6x12-in. (152x305 mm) cylinders prior to testing. These values are given in Tables 2 and 3.

In some tests, both wall panels were reinforced at the ends with 6x6-W2.9xW2.9 reinforcement to limit splitting. The total amount of reinforcement provided in each wall was 0.116 in.^{2} (75 mm^2).

C.2.3 Grout and Mortar

Grout strength was one of the major variables. Tests were made with grout strengths of approximately 3000, 5000, and 7000 psi. (20.7, 34.5 and 48.3 MPa). Actual compressive strengths are listed in Tables 2 and 3.

Laboratory tests were made to determine the properties of fine aggregate and fluid grout prior to starting the test program on full-scale joint specimens. These tests are described in Appendix D.

About 1-in. (25.4 mm) thick dry-packed mortar was placed under the top wall panel. The mixture contained equal parts by weight of Type I Cement and Elgin Sand, and just enough moisture to make it workable. Special metallic packers were used to ensure proper packing of the mortar layer.

Exposed edges of grout and dry-packed mortar were covered with plastic sheets for at least 3 days curing after they were placed. Compressive strength of dry pack was usually higher than that of wall panels and grout in the joint. A strength of about 9000 psi (62.1 MPa), was obtained from the average of six 2x2-in. (50x50 mm) cubes tested at an age of approximately 5 days.

C.3 Instrumentation

The test specimens were instrumented to measure forces, joint shortening, wall shortening and wall splitting. The layout of instrumentation for interior joint test is illustrated in Fig. 25. Test setup for exterior joints was similar. Due to the built-in eccentricity of the exterior joint, the slab was also supported horizontally and the horizontal reaction was measured.

C.3.1 Forces

In the case of Specimen JM-1 with long slabs, two sets of load cells[4] were used to measure the slab end reactions and the applied floor moment, as shown in Fig. 5. The slab load was applied with hydraulic rams.[3] Force was measured by a pair of load cells placed between the top of slab and the cross heads on both sides of the connection.

All other tests were conducted with short slabs. The support reactions were measured by two 25-kip (111 kN) load cells placed on concrete blocks under the slabs.

C.3.2 Joint and Wall Shortening

Three 1-in. (25 mm) Linear Variable Differential Transformers (LVDT)[4] were used to measure shortening of the joint, upper wall panel and the lower wall panel over a length of about 10 in. (0.25 m). Also, in some tests, an extra LVDT and a strain gage were used on the other side of the joint to measure shortening of the grout column alone.

C.3.3 Wall Splitting

Two 0.001-in. (0.025 mm) dial gages were used to measure upper and lower wall splitting. The gages were mounted to detect changes in wall thickness. Tensile strains were also sensed underneath the upper wall panel by two 67-mm gage-length electrical strain gages[3] mounted as shown in Fig. 25.

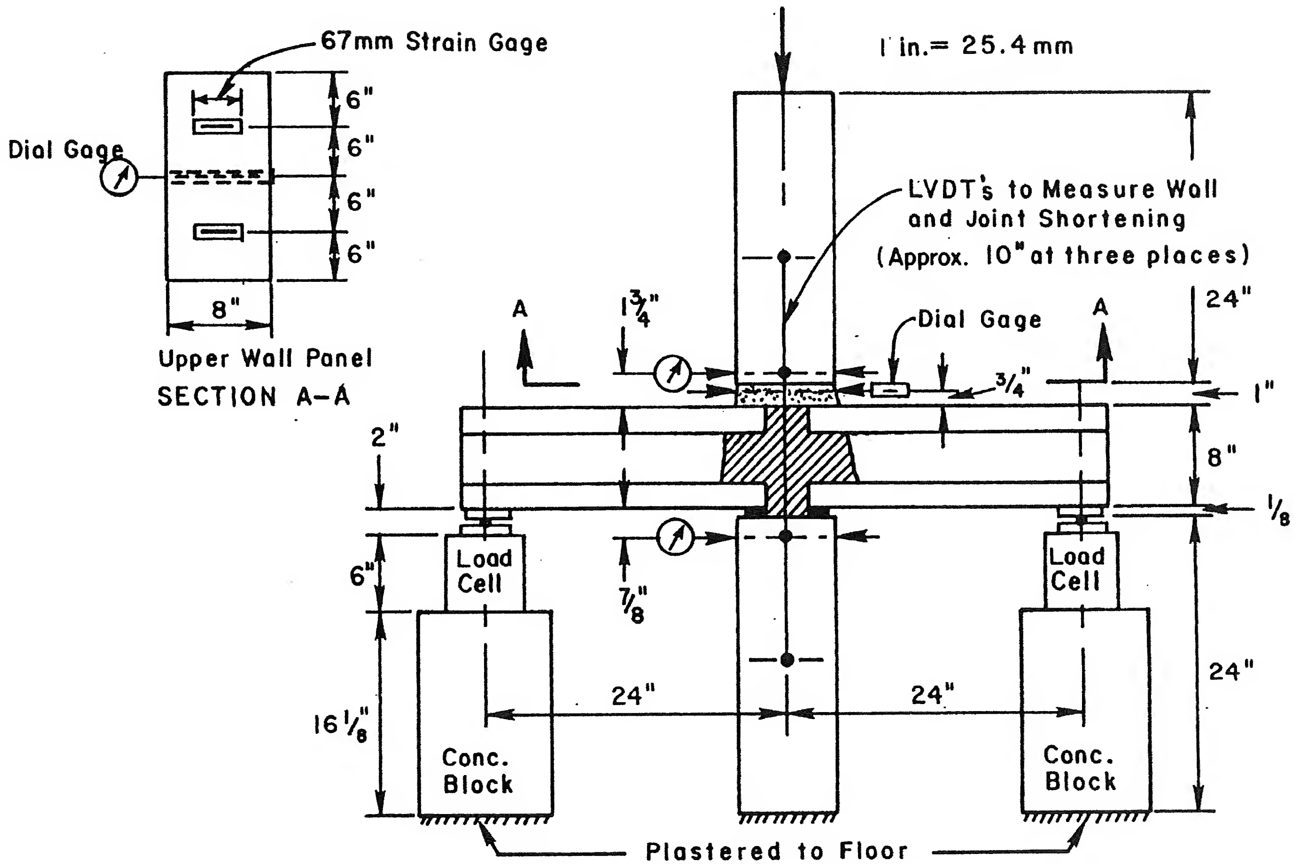


Fig. 25 Layout of Instrumentation for Interior Joint Test

An extra 0.001-in. (0.025 mm) dial gage was used to measure dry-pack opening due to vertical splitting.

All load cells, LVDT's and strain gages were connected to the Digital Data Acquisition System (DDAS). A mini computer was interfaced with DDAS system to obtain simultaneously a magnetic tape record and printout of raw data. The dial gages were recorded manually.

C.4 Test Procedure

Test setup and loading arrangement are shown in Figs. 7 and 8 for interior and exterior joints, respectively. A 1,000,000 lb. (4448 kN) testing machine was used to apply the vertical compressive force. Load was applied through a 1-in. (25.4 mm) thick steel plate plastered to the top of the upper wall panel. The specimen was centered below the loading head.

Specimens were loaded incrementally to destruction. The loading head of the machine was locked by inserting wedges after two or three load stages.

Each specimen was loaded in about 25 increments. The size of increment was reduced as the ultimate strength was approached.

After each load increment, measurements of all data were recorded. Cracks were identified and marked on the specimen in the order of their formation. Any other characteristics that occurred in the specimen after the initiation of the cracks were recorded also. The maximum load sustained was considered as the strength of the joint.

APPENDIX D - GROUT TEST SERIES

by

L. S. Johal and E. F. P. Burnett*

D.1 Test Program

The main objective of the tests was to determine the properties of grout used to fill both longitudinal and transverse joints in LP structures. Compressive strengths were measured on 2-in. (51 mm) cubes, 2x4-in. (51x102 mm) cylinders and 6x12-in. (152x305 mm) cylinders at 7 and 28 days. Tensile splitting tests were made on 2x4-in. (51x102 mm) cylinders at the same ages.

The main variables included were:

1. Aggregate to cement ratio.
2. Water to cement ratio.

The test program consisted of two series. Series A used an aggregate to cement ratio, by volume, of 3.0. Series B used a ratio of 2.25. For each series, the water to cement ratio, by weight, was varied from 0.375 to 0.75. Amounts of materials used for each batch of grout are shown in Table 10. Since there was always some free moisture present in aggregates, an approximate adjustment was made each time to the amount of water added to the mix.

TABLE 10 - GROUT CONSTITUENTS AND MIX WEIGHTS

Materials	Bulk Unit Weight lb./cu. ft.	Mix Weights, lb.	
		Series A	Series B
Type I Cement	94	40	40
Elgin Sand F.M. = 3.10	101	130	96
Water	62.4	Varied	Varied

Metric Equivalents: 1 lb. = 4.448N
1 cu. ft. = 0.02832 cu.m.

*Respectively, Construction Engineer, Construction Methods Section and Visiting Senior Structural Engineer, Structural Development Section, Portland Cement Association, Old Orchard Road, Skokie, Illinois.

Test specimens were cast following ASTM specifications C780-74, "Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry."(6) They were cured in the moulds covered with plastic sheets for about 48 hours after fabrication. The specimens were then demolded and stored in the moist room until about two hours before testing. The ends of cylindrical specimens for compression tests were capped with high strength capping compound and the caps were allowed to cure at least one hour prior to compression testing. The strengths of grout were determined from the average of at least four specimens.

D.2 Test Results

Average grout strength versus water-cement ratio are shown in Figs. 26 through 29. Average values for each series are given in Table 11.

The tests indicated that when the grout was either too stiff or too fluid, the results were inconsistent. When the water-cement ratio was low, compaction was a problem, and inconsistency resulted from a nonuniform mix. With high water-cement ratio, the mix was very fluid. Compaction was not required. However, heavier particles tended to settle down leaving a thick layer of water on top. Also, the mix had to be constantly agitated while the specimens were being cast.

Based on these tests, it appears that the most appropriate water-cement ratio to achieve good workability and consistency would be in the range of 0.5 to 0.75 with an aggregate-cement ratio of 3.0, and between 0.375 and 0.625 for an aggregate-cement ratio of 2.25.

Tests were also made to determine the fineness modulus, moisture content, unit weight, and specific gravity of sand that was used as fine aggregate in grout mix. The results of tests on fine aggregate are tabulated in Table 12. The gradation curve shown in Fig. 30, was plotted from the results of standard sieve analysis. The material conformed to the ASTM requirements.(7)

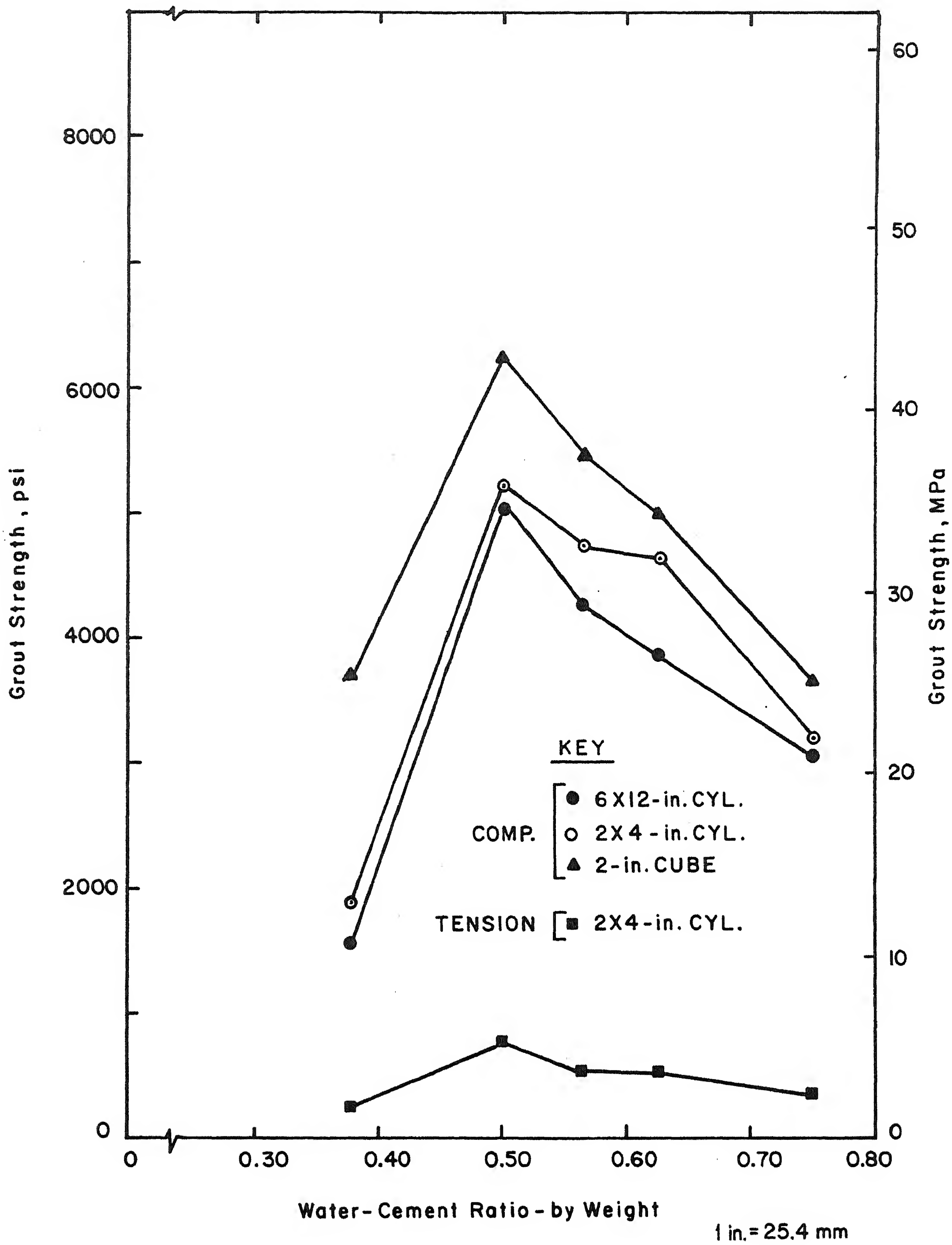


Fig. 26 Strength versus Water-Cement Ratio at 7 Days for Series A

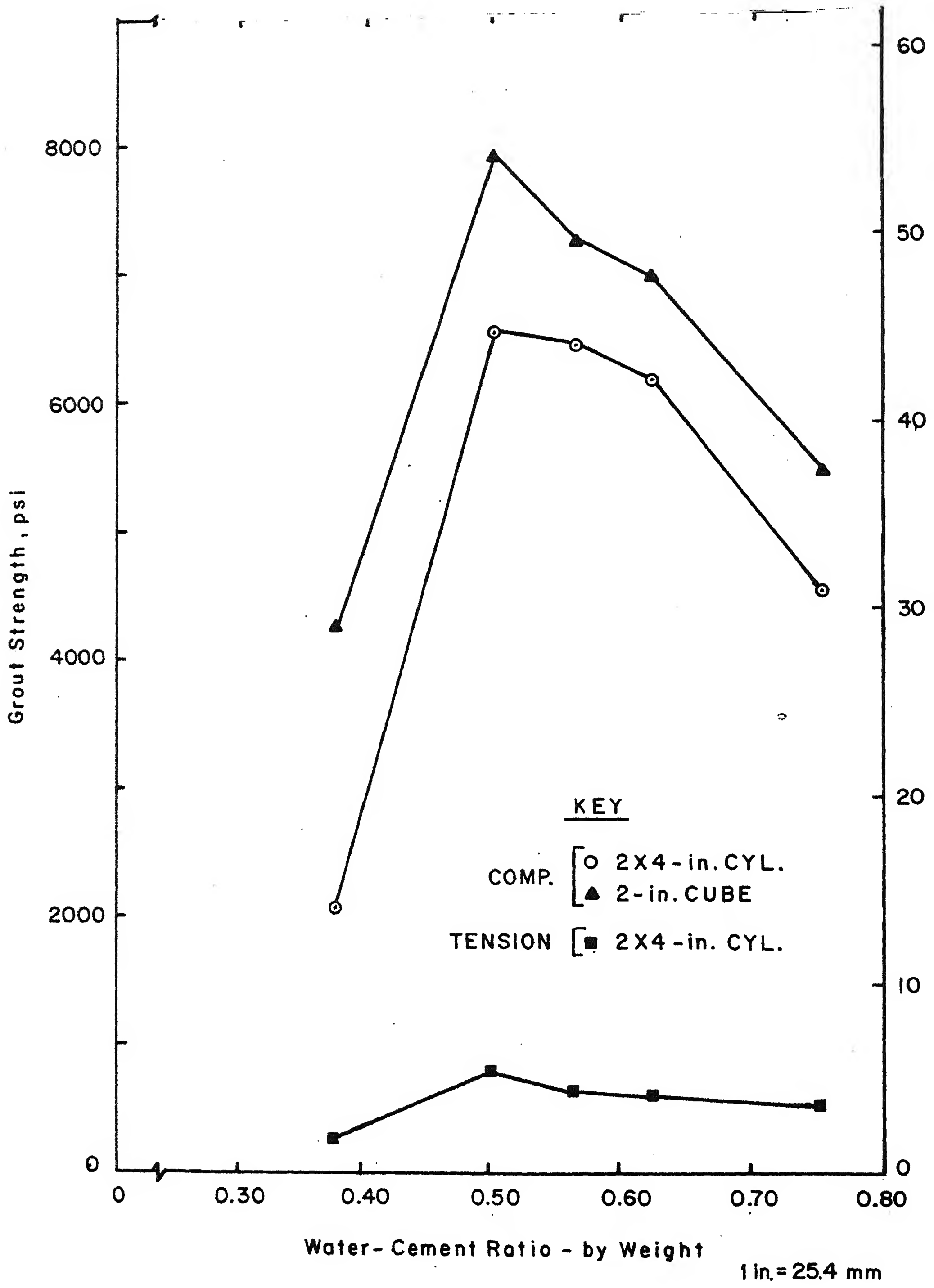


Fig. 27 Strength versus Water-Cement Ratio at 28 Days for Series A

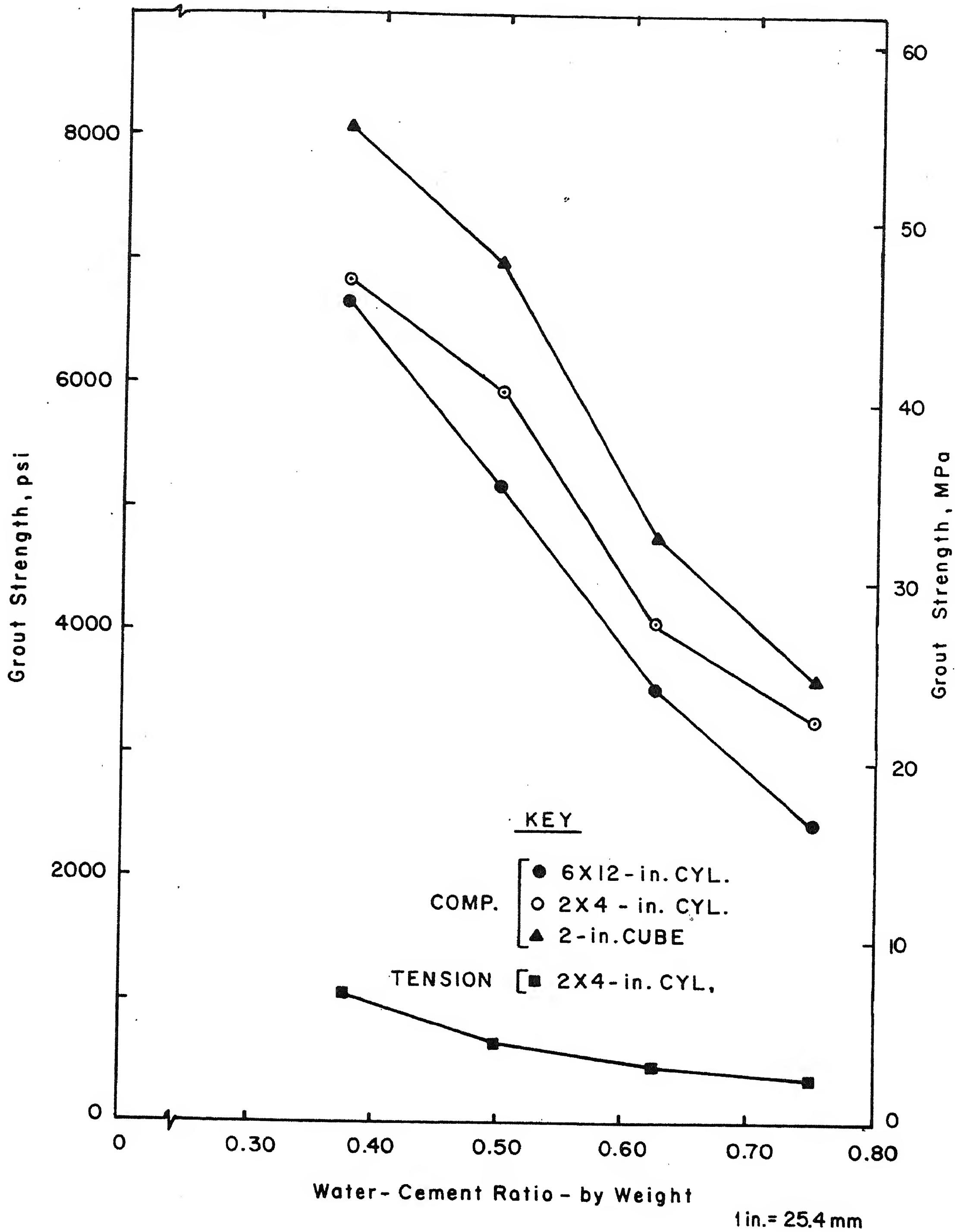


Fig. 28 Strength versus Water-Cement Ratio at 7 Days for Series B

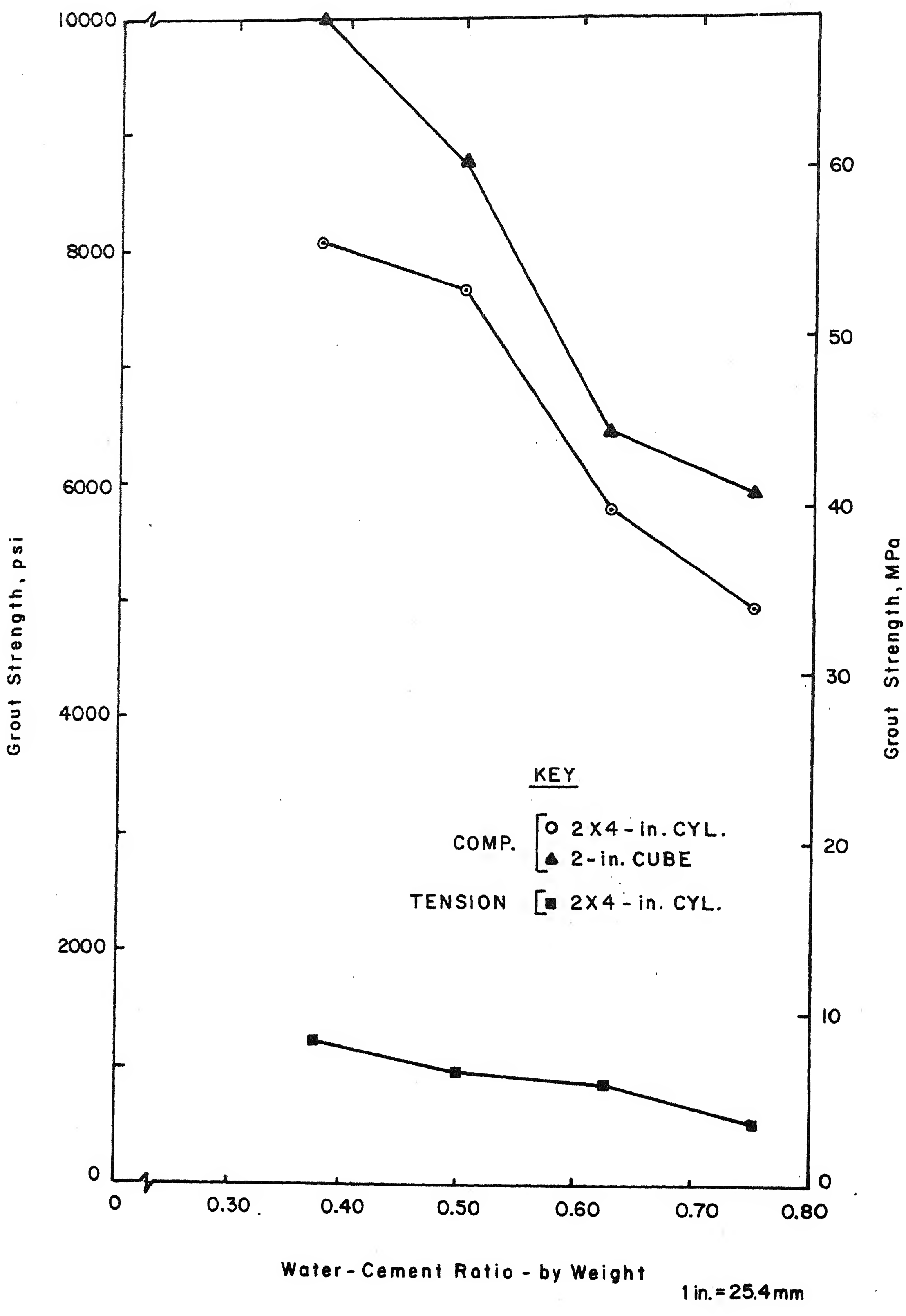


Fig. 29 Strength versus Water-Cement Ratio at 28 Days for Series B

TABLE 11 - AVERAGE STRENGTHS - GROUT SERIES A AND B

Aggregate-Cement Ratio (by volume)	Water-Cement Ratio (by weight)	Average Compressive Strength* (psi)					Avg. Tensile Strength* (psi)	
		2-in. Cubes		2x4-in. Cyl.		6x12-in. Cyl.	2x4-in. Cyl.	
		7 Days	28 Days	7 Days	28 Days	7 Days	7 Days	28 Days
3.0	0.375	3700	4240	1880	2070	1550	250	270
	0.500	6220	7890	5190	6510	5040	770	800
	0.562	5490	7220	4720	6490	4250	530	650
	0.625	4990	6960	4610	6170	3880	510	620
	0.750	3610	5460	3180	4510	3060	360	540
2.25	0.375	8050	10000	6830	8050	6640	1040	1240
	0.500	6970	8750	5920	7660	5130	650	980
	0.625	4710	6410	4030	5790	3550	480	860
	0.750	3570	5900	3240	4940	2400	350	510

* Average strength of at least four specimens.

Metric Equivalents: 1 in. = 25.4 mm
1 psi. = 6.89 kPa

TABLE 12 - PROPERTIES OF FINE AGGREGATE

Fineness Modulus		3.10
Moisture Content		3.14 %
Specific Gravity		2.73
Unit Weight (pcf)	Natural	101
	Dry	115

Metric Equivalent: 1 pcf = 16.02 kg/cu.m

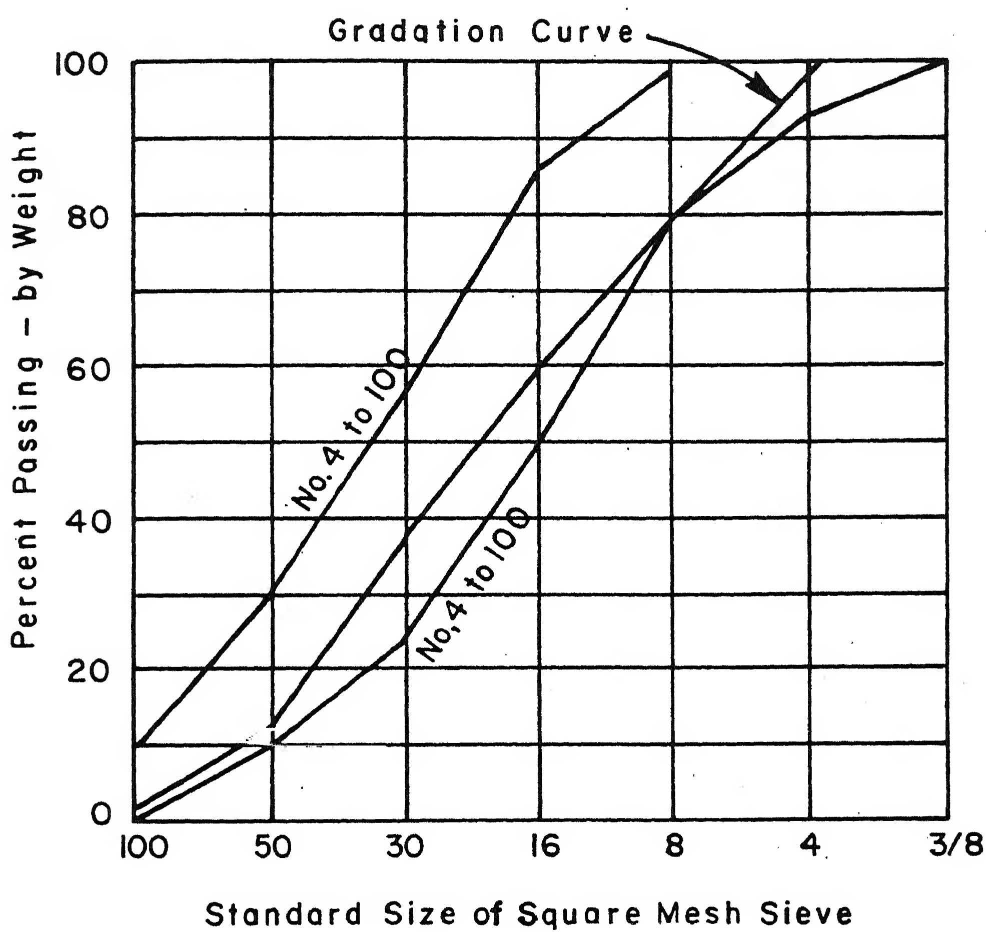


Fig. 30 Gradation Curve for Fine Aggregate

ACKNOWLEDGEMENTS

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METRIC CONVERSION FACTORS

The following list will enable readers to convert the U.S. and Canadian customary values of measurements used in this publication to SI (International System) units, the currently recommended form of the metric system. Also included are a few conversion factors that do not conform strictly to SI but are commonly used in some "metric" nations. The proper conversion procedure is to multiply the specified U.S. or Canadian customary value by the conversion factor exactly as given below and then to round to the appropriate number of significant digits desired. For example, to convert 11.4 ft. to meters: 11.4 x 0.3048 = 3.47472 which rounds to 3.47 meters for an accuracy of two significant digits. Do not round either value before performing the multiplication, as accuracy would be reduced. A complete guide to the SI system and its use can be found in ASTM E380, Standard Metric Practice Guide (A Guide to the Use of SI--the International System of Units).

To convert from	to	multiply by
Length		
inch (in.)	centimeter (cm.)	2.54 E*
inch (in.)	meter (m.)	0.0254 E
foot (ft.)	meter (m.)	0.3048 E
yard (yd.)	meter (m.)	0.9144 E
Area		
square foot (sq.ft.)	square meter (sq.m.)	0.09290
square inch (sq.in.)	square centimeter (sq.cm.)	6.452
square inch (sq.in.)	square meter (sq.m.)	0.0006452
square yard (sq.yd.)	square meter (sq.m.)	0.8361
Volume		
cubic inch (cu.in.)	cubic centimeter (cu.cm.)	16.39
cubic inch (cu.in.)	cubic meter (cu.m.)	0.00001639
cubic foot (cu.ft.)	cubic meter (cu.m.)	0.02832
cubic yard (cu.yd.)	cubic meter (cu.m.)	0.7646
gallon (gal.) Can. liquid**	liter	4.546
gallon (gal.) Can. liquid**	cubic meter (cu.m.)	0.004546
gallon (gal.) U.S. liquid**	liter	3.785
gallon (gal.) U.S. liquid**	cubic meter (cu.m.)	0.003785
Force		
kip	kilogram (kgf)	453.6
kip	newton (N)	4,448.
pound (lb.)	kilogram (kgf)	0.4536
pound (lb.)	newton (N)	4.448
Pressure or Stress		
kip per square inch (ksi)	kilogram per square centimeter (kg/sq.cm.)	70.31
pound per square foot (psf)	kilogram per square meter (kg/sq.m.)	4.882
pound (force) per square foot (psf)	pascal (Pa.)†	47.88
pound per square inch (psi)	kilogram per square centimeter (kg/sq.cm.)	0.07031
pound (force) per square inch (psi)	pascal (Pa.)†	6,895.
Mass (Weight)		
pound (lb.) avdp.	kilogram (kg)	0.4536
ton, 2,000 lb.	kilogram (kg)	907.2
grain	kilogram (kg)	0.00006480
Mass (weight) per Length		
kip per linear foot (klf)	kilogram per meter (kg/m.)	0.001488
pound per linear foot (plf)	kilogram per meter (kg/m.)	1.488
Mass per Volume (Density)		
pound per cubic foot (pcf)	kilogram per cubic meter (kg/cu.m.)	16.02
pound per cubic yard (pcy)	kilogram per cubic meter (kg/cu.m.)	0.5933
Temperature		
degree Fahrenheit (deg. F.)	degree Celsius (C)	$t_C = (t_F - 32)/1.8$
degree Fahrenheit (deg. F.)	degree kelvin (K)	$t_K = (t_F + 459.7)/1.8$
Energy		
British thermal unit (Btu)	joule (J)	1,056.
kilowatt-hour (kwh)	joule (J)	3,600,000. E
Power		
horsepower (hp) 550 ft.-lb./sec.	watt (W)	745.7
Velocity		
mile per hour (mph)	kilometer per hour	1.609
mile per hour (mph)	meter per second (m./s.)	0.4470

*E indicates that the factor given is exact.
**One U.S. gallon equals 0.8327 Canadian gallon.
†A pascal equals 1.000 newton per square meter.